COLLEGE PHYSIOGRAPHY

THE MACMILLAN COMPANY
NEW YORK · BOSTON · CHICAGO · DALLAS
ATLANTA · SAN FRANCISCO

MACMILLAN & CO., LIMITED
LONDON · BOMBAY · CALCUTTA
MELBOURNE

THE MACMILLAN CO. OF CANADA, LTD.
TORONTO

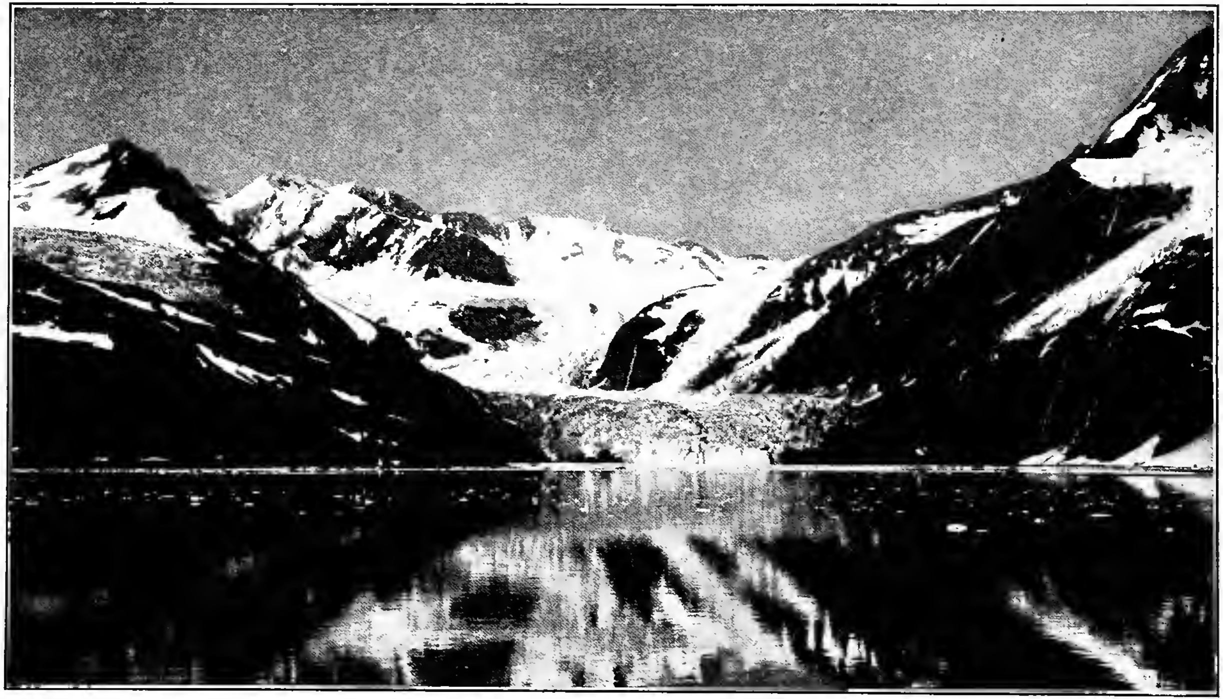


Fig. 1.—Surprise Glacier in Harriman Fiord among the Mountains of Prince William Sound, Alaska.

COLLEGE PHYSIOGRAPHY

BY

RALPH STOCKMAN TARR

LATE PROFESSOR OF DYNAMIC GEOLOGY AND PHYSICAL GEOGRAPHY
IN CORNELL UNIVERSITY

PUBLISHED UNDER THE EDITORIAL DIRECTION

OF

LAWRENCE MARTIN

ASSOCIATE PROFESSOR OF PHYSIOGRAPHY AND GEOGRAPHY
IN THE UNIVERSITY OF WISCONSIN

New York
THE MACMILLAN COMPANY
1914

Set up and electrotyped. Published September, 1914.

Norwood Press
J. S. Cushing Co. — Berwick & Smith Co.
Norwood, Mass., U.S.A.

EDITOR'S PREFACE

THIS text-book of College Physiography is written for use in elementary physical geography courses in universities, colleges, and normal schools, for supplementary reference-reading by high school students who are using a more elementary text, and for general reading by laymen of mature years.

The plan of the book is to present, in order, (1) the geographical features of the earth as a planet, (2) the processes in operation and the topographic forms in existence on the lands, (3) the physical geography of the ocean, and (4) the nature and effects of the atmosphere. Combined with each of these are illustrations of the relations of physical geography to life and especially to man.

No attempt has been made to cover all topics simply because they are usually included in a course in physical geography. Instead, each topic is discussed where it naturally comes up in the logical development of the subject. It is assumed that a certain elementary knowledge, for example of latitude, longitude, standard time, the seasons, etc., is retained from grammar school geography or high school physiography. They will naturally be reviewed in the laboratory work of a good course in college physiography or, when necessary, can be looked up in a school geography. For schools desiring a shorter list of assignments than is here presented, an abridgment might be accomplished by omitting such matters as the Specific Instances of Volcanic Eruptions (pp. 449–475), Relief Features of the Earth (Chapter XVI), or the Earth's Interior (Chapter XVII). It is desirable that both field and laboratory work accompany the study of the text. For courses in advanced physiography or geomorphology, the study of the maps and the reading of selected papers from the original sources listed at the ends of the chapters is recommended. The photographs and diagrams in the text have been chosen with great care and are as well worth study as the text itself.

The book was written by the late Professor Tarr, chiefly during the winter 1910–11, although there are indications that he began work on it as early as 1895. He had completed the first draft of the manuscript dealing with the earth as a planet, the lands, and the ocean before his death on March 21, 1912. He died suddenly and left no directions as to the disposal of this manuscript. With the approval of Mrs. Tarr and after conference with several of Professor Tarr's more intimate friends among the geographers of the United States, the editor undertook the task of preparing the book for publication. He edited the existing manuscript, added data in connection with new discoveries in physical geography, prepared the illustrations and the bibliographies and map lists at the ends of the chapters, and wrote seven chapters to complete the book. These are the chapters dealing with the atmosphere and with terrestrial magnetism. In writing the original twenty chapters the author had followed the outline of the printed syllabus of his course in elementary physical geography at Cornell University. Accordingly this syllabus has been followed in the new chapters, amplified by as many as possible of the illustrative features which Professor Tarr used in his work of instruction at Cornell. In preparing the bibliographies and map lists, use was made of such materials as were left by Professor Tarr, some of them partly drawn up on catalogue cards for use in this book and some published in earlier books, together with some from the editor's own materials used in instruction at the University of Wisconsin. In all respects he sought to carry out the plan and style of presentation which he thought Professor Tarr would have followed in completing the book. In addition to five years of study and teaching at Cornell University the editor had the privilege of intimate association with Professor Tarr in four summers of field work in Alaska and in New York. He also assisted the author in clerical work while he was preparing three of his text-books and collaborated with him in writing two scientific books and a number of technical and popular articles. With this experience in mind constantly, the editor has striven to complete the book along the lines which the author would have followed, although with obvious imperfections in execution.

As a matter of professional acknowledgment the editor does not feel that he can do better than to quote the author's own words, from the preface of Tarr's New Physical Geography, written eleven years ago. "It goes without saying that the author is profoundly indebted to the host of workers in physiography, from whom he has drawn so much inspiration, suggestion, and fact: Gilbert, Davis, Powell, Geikie, Penck, de Lapparent, Russell, Shaler, Dutton, Chamberlin, Hayes, Campbell, Salisbury, Brigham, Dodge, Dryer, and many others. From the writings of these physiographers the author has culled whatever seemed to him suited to a scheme of elementary instruction; and so numerous, and often so unconscious, is the influence of these fellow-workers, that specific acknowledgment would be quite impossible. Doubtless the most profound influence upon the author is that of his two teachers, Professors Shaler and Davis, the importance of which to him cannot be overestimated. Together with other physiographers, the author further recognizes in Professor Davis a leader in American physiography, from whom even some of the fundamental principles of the subject have been derived. An examination of the following pages would show the influence of this physiographer in many places, an influence not confined to the pure science, but extending to the pedagogy of the subject as well."

The illustrations, many of which are new, are taken from photographs by the author, or pictures taken under his direction by J. O. Martin of Wilbraham, Mass., by O. D. von Engeln of Ithaca, N.Y., by the editor of this volume, and others. A number were purchased for use in this and earlier books by the author, the collections of certain American physiographers, and of the United States Geological Survey, the department of geology at Cornell University, W. H. Rau of Philadelphia, F. J. Haynes of St. Paul, S. R. Stoddard of Glens Falls, N.Y., and the Detroit Photographic Company supplying a great many. The photographer's name, where known, appears in the legends of the illustrations. Most of the foreign photographs were purchased in Europe by the author. Many of the photographs by the author and the editor were taken under the auspices of the National Geographic Society of Washington, the American Geographical Society of New York, and the United States Geological Survey. Most of the models are by the late E. E. Howell of Washington. A large proportion of the block diagrams were drawn by C. W. Furlong of Boston. Mr. E. F. Bean of the University of Wisconsin helped materially in preparing the illustrations.

Acknowledgment is particularly due to Professor R. de C. Ward of Harvard University, who was good enough to read the manuscript of the six chapters dealing with the atmosphere, and to Dr. L. A. Bauer of the Carnegie Institution of Washington, who kindly read the manuscript of the chapter on terrestrial magnetism. Each of these gentlemen made valuable criticisms and suggestions, but the editor takes full responsibility for any shortcomings in these chapters.

The editor feels keenly the responsibility which he is incurring by preparing this book for the press, for the author's reputation is so high that nothing should be done that could possibly mar it. Professor Tarr prepared only the first draft of twenty out of the twenty-seven chapters. His experience in twenty years of college teaching, his facility in writing, and especially in writing three successful high school physiographies, a laboratory manual of physical geography, an elementary geology, an economic geology of the United States, a series of grammar school geographies, a regional geography of his own state, three scientific books on physiography, glaciers, and earthquakes in Alaska, and scores of technical and popular articles, based upon his investigations in various parts of North America and Europe, all qualified him to produce a book of the first quality. Had he lived to complete it, there would surely be an improvement along many lines; but, as it is, the book must stand upon its merits.

LAWRENCE MARTIN.

MADISON, WISCONSIN,
July 13, 1914.

CONTENTS

LIST OF COLOURED MAPS

ACKNOWLEDGMENT OF ILLUSTRATIONS

In addition to the credit for illustrations given in the Preface and in the legends of the half tones and text figures, acknowledgment is due the following authors and publishers for kindly permitting the use of illustrative material and, in several cases, for supplying electrotypes. The numbers below refer to figures in this book.

Bowman's *Forest Physiography*, John Wiley & Sons, New York, — Figs. 28, 183, 290, 351, 358, 362, 367, 378, 468.

Davis's *Elementary Meteorology*, Ginn & Co., Boston, — Figs. 429, 500.

Davis's *Erklärende Beschreibung der Landformen*, B. G. Teubner, Leipzig,— Fig. 150.

de Martonne's *Traité de Géographie Physique*, Armand Colin, Paris, — Figs. 379, 392, 412.

Encyclopædia Britannica, University of Cambridge Press,—Figs. 14, 77, 170, 387, 442.

Herbertson and Taylor's *Oxford Wall Maps*, Henry Frowde, London, — Fig. 486.

Hobbs's *Earth Features and their Meaning*, Macmillan Co., New York, — Figs. 36, 54, 59, 73, 139, 162, 164, 165, 166, 173, 181, 184, 190, 196, 221, 237, 255, 257, 261, 278, 279, 280, 283, 289, 296, 322, 336, 384, 433.

The editor of this volume, — (Photographs), Figs. 1, 122, 128, 136, 138, 151, 153, 175, 176, 202, 203, 231, 360, 363, 376; (Maps and Diagrams), Figs. 123, 126, 143, 154, 155, 156, 159, 195, 227, 272, 276, 286, 364, 377.

Milham's *Meteorology*, Macmillan Co., New York, — Figs. 424, 457, 465, 470, 477, 495, 498.

Moulton's *Introduction to Astronomy*, Macmillan Co., New York, — Figs. 7, 8, 389.

Murray and Hjort's *Depths of the Ocean*, Macmillan & Co., London, Fig. 398.

Murray's *The Ocean*, Henry Holt & Co., New York, — Figs. 390, 391, 395, 408, 413.

Scott's *Introduction to Geology*, Macmillan Co., New York, — Figs. 17, 211, 277, 292, 304.

Todd's *New Astronomy*, American Book Co., New York, — Fig. 11.

Ward's *Practical Exercises in Elementary Meteorology*, Ginn & Co., Boston, — Figs. 460, 502.

Ward's *Climate, Considered Especially in Relation to Man*, G. P. Putnam's Sons, New York, — Figs. 431, 435, 447, 483, 484, 492, 503.

Wyoming Historical and Geological Society; also Connecticut Geological and Natural History Survey, diagrams by J. Barrell, — Figs. 345, 346.

INTRODUCTION

THE EARTH SCIENCES

THE earth consists of three quite distinct portions, a solid central mass, a partial envelope of liquid, and a complete blanket of gases, each of which is the seat of a series of interesting phenomena. Their investigation has attracted the thoughtful attention of many scientific men, both in the past and at present. The study of the gaseous portion, or atmosphere, has led to the development of *Meteorology*, and one phase of this study has been recognized as the science of *Climatology*. The science of the study of the waters is called *Hydrography*, and of that larger part of the liquid envelope which occupies the ocean basins, *Oceanography*.

Several distinct sciences deal with the study of the solid earth itself. For example, *Mineralogy* concerns itself with the minerals of which this solid earth is composed; and *Petrology* with the study of the rocks of the earth; while the study of certain special phenomena has given rise to special sciences with limited scope, such as *Seismology*, which is concerned with a study of earthquakes, and *Vulcanology*, with volcanic phenomena. But the two chief sciences dealing with the solid earth are *Geology* and *Geography*, and each of these is concerned also, to a certain extent, with the waters and the air. These are, therefore, of broader scope than either of the other sciences, since they involve, to a degree, a consideration of the earth as a whole, not a single phase of it.

Geology deals with the past history of the earth and its development through the ages. Geography, on the other hand, is concerned with the present condition of the earth in its relation to life. One of the divisions of geography is called *Physical Geography*, or, sometimes, *Physiography*, which may be defined as *that science which investigates the physical features of the earth and their influence on life, especially man*. It is a fundamental part of geography, and basal to any scientific study of that subject. To some, it seems difficult of separation from geology, and in certain of its aspects it might indeed be considered the latest chapter in geology, — the history of the present surface of the earth, or *Geomorphology*. But it is broader than this, for it deals not merely with the latest chapter in the history of the earth, but also with the influence of the surface features on human and other life, and the interaction and interrelation between air, water, land, and life.

Physical geography is an integral part of geography, and not to be separated from it, having independent subrank under the larger whole, side by side with *Political Geography*, *Anthropogeography*, etc., and having for its special field the more physical aspects of geography, as its name indicates. Dealing as it does with air, land, and water, physical geography of necessity draws from meteorology, geology, and oceanography for some of its facts and methods, and even for some of its field of investigation. Did it not do so, it could be little more than a descriptive science, telling merely what the earth's surface is, and leaving to other sciences the statement of how it came to be. In the study of the land in particular, it is necessary to borrow from geology, for no interpretation of the present surface features is possible without a knowledge of at least some of the past events by which they have come to be.

The Principle of Vast Lapse of Time

One of the most fundamentally important contributions to an understanding of the history of the earth is the proof which geologists have presented of the vast lapse of time during which this earth history has been in progress. It is equally fundamental to an understanding and interpretation of the surface features of the earth with which physical geography has to do. So long as it was thought that the age of the earth was to be numbered in a few thousand years, no real progress was possible, either in unravelling its history or in interpreting the earth forms by which man is surrounded. It has now been demonstrated, by a series of proofs that are incontrovertible, that the age of the earth is to be reckoned in millions of years, and that even those slowly operating processes with which we are surrounded, and which, in a human life-time, may not cause visible change, are capable of performing vast tasks and of bringing about great changes, when in incessant operation through not merely hundreds of years, but tens of thousands and hundreds of thousands of years.

The acceptance of this principle, which during the last century required long and heated argument to establish, and the patient accumulation of a great mass of observations before it was finally and universally accepted even by scientific men, is fundamental to an appreciation of the phenomena of the surface of the earth. It is as basal a principle in geology and physical geography as a broad conception of the distances in space is basal to astronomy. In both cases the full appreciation of the conception is denied the human mind, for in his experience man deals only with inches, feet, and miles, and with seconds, minutes, and years. It is, therefore, quite beyond our power to fully realize the true significance of the $92\frac{3}{4}$ million miles which separate the sun and earth, or the scores of millions of years which separate us from the early ages of geological time. Yet the one is as truly a fact as the other, and neither the principles of astronomy nor of physical geography can be really appreciated without accepting as a basal principle the measure of the space or the time which lies far beyond our limited range of experience. The principle is so well established that it may fairly be stated as such without a preliminary attempt at proof; leaving the verification to appear as the subject is developed.

Development of Physical Geography

The development of science, in general, up to its present standard was primarily the work of the last century, though it was preceded by a series of brilliant discoveries, notably of basal principles in astronomy and physics. The study of the earth, partly descriptive, had occupied the attention of many workers in the preceding centuries; and naturally the phenomena of the earth upon which man lived, and by which he was surrounded, led to some investigation and to still more speculation, often most fantastic. Thus earthquakes, volcanoes, fossils in the rocks, and other phenomena early attracted attention and were subjects of investigation and speculation; and naturally the question of the origin of the earth itself was a source of interest and wonder which led to speculation, as is proved by the cosmologies of the ancients, and the even more vague speculations of more primitive peoples.

Although much thought had been given to the subject, and much had been written upon it and some important facts and principles had been put forward by the beginning of the last century, there had been little real progress in the development of any phase of earth science up to the beginning of the nineteenth century. This lack of progress was in part due to the general unorganized state of science. This affected all sciences to almost equal extent. It was even further due to the prevalence of the fundamental fallacy that the cosmology presented in the first chapter of *Genesis* was to be taken literally, and was to serve as the basal principle in an interpretation of earth history. It required more than ordinary evidence to overcome this fallacy, for it was given the stamp of infallibility by theological dogma. Any facts that seemed to controvert the Jewish cosmology must needs be thrown out; and any argument based upon such facts was regarded as an attack upon the very foundation of religious belief. There arose, therefore, a conflict between science and religion, or, as White better phrases it, a "Warfare of Science with Theology." This conflict just alluded to led to bitter controversy, increasing in extent and intensity in the first half of the nineteenth century, and not completely extinguished even in the second half, though now, happily, almost completely at an end.

There were also bitter controversies among geologists, of which one of the most serious was between the school of *Werner*, a German, and *Hutton*, a Scotchman. The former held that the earth had developed its present form with rapidity through a succession of catastrophic phenomena in which water was the prime agent, and the Wernerian School became known as the *Neptunists*. Hutton held that the present earth form was the result of slower evolution in which both water and heat were involved, and his school became known as the School of the *Vulcanists*. In its main elements, the theory of Hutton has prevailed; and to it we may look for some of the basal principles of the physical geography of the lands. Playfair's "Illustrations of the Huttonian Theory of the Earth," published in 1802, is the real beginning of the modern physical geography, for it postulates the idea of vast lapse of time in which "we can see neither the beginning nor the end," the importance of the forces at present in operation, when operating through long periods of time, the true origin of river valleys, and other basal principles of physical geography.

For a generation, so bitter was the controversy, and so opposed was the Huttonian theory to the supposed demands of true religion, that the brilliant assemblage of facts and logical deductions from them put forward by Hutton, Playfair, and others, failed of acceptance and apparently left little or no impression upon the science of the time. The Huttonian theory was revived, elaborated, and amplified in 1830 in Lyell's "Principles of Geology." He fostered it with all the vigour of his brilliant mind. Primarily by Lyell's work, aided by the researches of a number of other students of earth science, the Huttonian principle became established, and the doctrine of *Uniformitarianism*, as opposed to that of *Catastrophism* presented. With some modification in detail it is basal to the study of the development of the surface forms of the earth. This doctrine holds that by the processes of the present, working through the lapse of time, the present features of the earth have been evolved; and that catastrophes, though probably occurring, are not essential to the underlying causes.

In the further development of physical geography a multitude of workers have taken part in bringing it to its present standard. This is not the place to attempt to trace the development of the subject in detail, nor to list the names and contributions of the principal workers. The names of three Americans, — Gilbert, Powell, and Davis, — however, stand out with such special prominence in the history of the development of modern physical geography that they call for mention even in this generalized view. In two reports, written at about the same time, 1875, — Gilbert's chapter on Land Sculpture in "The Geology of the Henry Mountains" and Powell's "Exploration of the Colorado River of the West," — there are stated for the first time some of the underlying principles of land sculpture, upon which the scientific study of the surface of the earth is based. Professor Davis has added still other principles, has outlined and developed the idea of the progressive stage in the development of land forms, and has given to physical geography an organization which has won many followers, including the writer of this book, who was fortunate enough to be one of his early pupils, and at the same time to come under the inspiring influence of that great teacher and geographer, Professor N. S. Shaler. Some of Professor Davis's papers have been collected in a single volume entitled "Geographical Essays," 1909; see also Davis's "Physical Geography," 1898; "Practical Exercises in Physical Geography," 1908; "Grundzüge der Physiogeographie," 1911; "Erklärende Beschreibung der Landformen," 1912.

In a study of the air and of the oceans, as well as of the lands, many men have been at work, and the development of the sciences of the air, ocean, and land is dependent upon the combined effort of them all, though with some more potent than others in the discovery, verification, and exposition of underlying principles. Modern physical geography has developed out of the work of this army of students, specific reference to some of whose contributions will appear in the succeeding chapters of this book.

References to Literature

The literature of physical geography is extensive. Among the writings upon the subject are elementary school textbooks, special articles upon particular processes or areas, books upon special topics such as rivers, earthquakes, etc., books and articles relating specifically to the atmosphere and the oceans, and books of a general nature. Reference to all but the first of these classes of publications will be found in later pages, but there are a number of publications of such a general nature that they are listed below, mainly of books and magazines, relating specifically to the Physical Geography of the Lands, deferring reference to the atmosphere and oceans to those sections dealing specifically with these topics. The list also includes a few books on human geography. This subject is discussed incidentally throughout the book along the line of the splendid contributions by Friedrich Ratzel, Elisée Réclus, J. Brunhes, and others in Europe, and Miss E. C. Semple, A. P. Brigham, and others in America. It is not claimed that the following list is complete, nor that it has included all that are of importance and value.

PHYSICAL GEOGRAPHY

John Playfair. Illustrations of the Huttonian Theory of the Earth, Edinburgh, 1802.
Karl Ritter. Die Erdkunde, Berlin, 1817.
Sir Charles Lyell. Principles of Geology, 1st edition, 1830; 11th edition, 2 vols., New York, 1873.
A. von Humboldt. Cosmos, 1844; edition in English, 5 vols., London, 1871–1872.
J. P. Lesley. Manual of Coal and its Topography, Philadelphia, 1856.
J. W. Powell. Exploration of the Colorado River of the West, Chapters XI and XII, Washington, 1875.
G. K. Gilbert. Report on the Geology of the Henry Mountains, Chapter V, Washington, 1877.
T. H. Huxley. Physiography, London, 1877.
O. Peschel and G. Leipoldt. Physische Erdkunde, 2 vols., Leipzig, 1880.
F. von Richthofen. Führer für Forschungsreisende, Berlin, 1886, 1901.
A. Geikie. The Scenery of Scotland, London, 1887.

G. de la Noë and Emm. de Margerie. Les Formes du Terrain (with atlas of plates), Service Geographique de l'Armée, Paris, 1888.
N. S. Shaler. Aspects of the Earth, New York, 1889.
S. Günther. Lehrbuch der Physikalischen Geographie, Stuttgart, 1891; Handbuch der Geophysik, 2 vols., Stuttgart, 1897, 1899.
H. R. Mill. The Realm of Nature, New York, 1892.
T. G. Bonney. Story of Our Planet, London, 1893.
J. Geikie. Fragments of Earth Lore, Edinburgh, 1893.
N. S. Shaler. Sea and Land, New York, 1894.
A. Penck. Morphologie der Erdoberfläche, 2 vols., Stuttgart, 1894.
J. W. Powell and Others. Physiography of the United States, National Geographic Monographs, New York, 1896.
Andrew D. White. History of the Warfare of Science with Theology in Christendom, 2 vols., New York, 1896.
A. de Lapparent. Leçons de Géographie Physique, Paris, 1896.
C. R. Dryer. Studies in Indiana Geography, Terre Haute, 1897.
E. Brückner. Die Feste Erdrinde und ihre Formen, Leipzig, 1897.
N. S. Shaler. Outlines of the Earth's History, New York, 1898.
J. Geikie. Earth Sculpture, London, 1898.
Henry Gannett. Topographic Atlas of the United States. U. S. Geol. Survey, — Folios 1 and 2, Physiographic Types, 1898, 1900; Folio 3, Physical Geography of the Texas Region, by R. T. Hill.
J. E. Marr. The Scientific Study of Scenery, New York, 1900.
A. J. Herbertson. Outlines of Physiography, London, 1901.
R. S. Tarr. The Physical Geography of New York State, New York, 1902.
J. Lubbock (Lord Avebury). The Scenery of England, New York, 1902.
A. Robin. La Terre, Paris, 1902.
H. Wagner. Lehrbuch der Geographie, 7th edition, Leipzig, 1903.
E. Suess. Das Antlitz der Erde; edition in English, "The Face of the Earth," translated by Sollas, 4 vols., Oxford, 1904–1912; the French edition, "La Face de la Terre," translated under the direction of the eminent Emm. de Margerie, is the best of the three because of the many additional illustrations and references to literature.
A. Hettner. Grundzüge der Länderkunde, Vol. I, Europe, Leipzig, 1907.
J. van Baren. De Vormen der Aardkoorst, Groningen, 1907.
R. D. Salisbury. Physiography, New York, 1907.
R. D. Salisbury and W. W. Atwood. The Interpretation of Topographic Maps, Prof. Paper 60, U. S. Geol. Survey, Washington, 1908.
J. W. Gregory. Geography — Structural, Physical, and Comparative, London, 1908.
W. M. Davis. Practical Exercises in Physical Geography (with atlas), Boston, 1908.
E. de Martonne. Traité de Géographie Physique, Paris, 1909, 1913.
Gen. Berthaut. Topologie, Étude du Terrain, 2 vols., Service Géographique de l'Armée, Paris, 1909.
W. M. Davis. Geographical Essays, Boston, 1909.
A. Supan. Grundzüge der Physischen Erdkunde, Leipzig, 1911.
W. M. Davis. Erklärende Beschreibung der Landformen, Leipzig, 1912.
S. Passarge. Physiologische Morphologie, Mitt. Geog. Gesell. in Hamburg, Band 26, Heft 2, 1912.
J. Brunhes, E. Chaix, Emm. de Martonne and Others. Atlas Photographique des Formes du Relief Terrestre, Geneva, 1914 to date.

HUMAN GEOGRAPHY

Arnold Guyot. The Earth and Man, Boston, 1849.
Karl Ritter. Geographical Studies, Boston, 1863; Comparative Geography, Philadelphia, 1865.

G. P. Marsh. The Earth as Modified by Human Action, New York, 1863, 1874.
O. Peschel. Races of Man, New York, 1876.
E. Réclus. La Terre, 2 vols.; Nouvelle Géographie Universelle, 19 vols., Paris, 1878–1895,— published in English as The Earth and Its Inhabitants; L'Homme et La Terre, 6 vols.
E. A. Freeman. Historical Geography of Europe, London, 1881, 1903.
J. Lubbock (Lord Avebury). Origin of Civilization, New York, 1886.
A. Kirchhoff. Unser Wissen von der Erde, 5 vols., Leipzig, 1886–1890; Man and Earth, London, 1906.
G. G. Chisholm. Handbook of Commercial Geography, 1st edition, 1889; 6th edition, London, 1906.
F. Ratzel. Anthropogeographie, 2 vols., Stuttgart, 1891, 1899; The History of Mankind, 3 vols., New York, 1896–1898; Die Erde und Das Leben, 2 vols., Leipzig, 1901; Politische Geographie, 2d edition, Munich, 1903.
N. S. Shaler. Nature and Man in America, New York, 1891; Man and the Earth, New York, 1905.
E. Stanford. Compendium of Geography and Travel, 2d edition, 12 vols. 1893–1901.
A. H. Keane. Ethnology, 2 vols., New York, 1896; Man, Past and Present, New York, 1899.
W. Z. Ripley. Races of Europe, 2 vols., New York, 1899.
H. R. Mill and Others. International Geography, New York, 1899.
H. B. George. Relations of Geography and History, Oxford, 1901.
H. J. Mackinder. Britain and the British Seas, New York, 1902.
A. P. Brigham. Geographic Influences in American History, Boston, 1903; From Trail to Railway Across the Appalachians, Boston, 1907.
J. Partsch. Central Europe, New York, 1903.
E. C. Semple. American History and Its Geographic Conditions, Boston, 1903; Influences of Geographic Environment, New York, 1911.
A. Geikie. Landscape in History, and Other Essays, London, 1905.
J. Brunhes. La Géographie Humaine, Paris, 1910.
H. E. Gregory, A. G. Keller, and A. L. Bishop. Physical and Commercial Geography, Boston, 1910.
C. R. Van Hise. Conservation of Natural Resources in the United States, New York, 1910; Mineral Resources in Civilization (in press).
J. R. Smith. Industrial and Commercial Geography, New York, 1913.

PERIODICALS

Bulletin of the American Geographical Society, New York.
Annals of the Association of American Geographers.
Geographical Journal, London.
Scottish Geographical Magazine, Edinburgh.
Annales de Géographie, Paris.
La Géographie, Paris.
Revue de Géographie, Paris.
Petermann's Mitteilungen, Gotha, Germany.
Zeitschrift der Gesellschaft für Erdkunde zu Berlin.
Geographische Zeitschrift, Leipzig.
Mitteilungen der Geographischen Gesellschaft in Wien.
Bollettino della Reale Società Geografica, Rome.
Bulletin of the Geographical Society of Philadelphia.
Appalachia, Boston.
National Geographic Magazine, Washington.
Geographical Teacher, London.
Journal of Geography, Madison, Wisconsin.

BIBLIOGRAPHIES

U. S. Geological Survey. Catalogue and Index of Contributions to North American Geology, 1732–1891, — Bulletin 127, U. S. Geol. Survey, 1896, by N. H. Darton; the same continued from 1892 to 1912 by F. B. Weeks and by J. M. Nickles as Bulletins 188, 189, 301, 372, 409, 444, 495, 524, and 545.

Royal Society of London. International Catalogue of Scientific Literature, annual bibliographies of Geography and Geology.

Gesellschaft für Erdkunde zu Berlin. Bibliotheca Geographica, published annually.

Geographisches Jahrbuch and *Geographen Kalendar,* Gotha, Germany.

Annales de Géographie. Bibliographie Géographique annuelle.

Geographical Association. Guide to Geographical Books and Appliances, by H. R. Mill, A. J. Herbertson, and others, London, 1910.

COLLEGE PHYSIOGRAPHY

PART I. THE PLANET AND THE LANDS

CHAPTER I

FUNDAMENTAL GENERAL FACTS

THE EARTH AS A PLANET

The Solar System. — The earth is one of a vast number of spheres in space, about most of which relatively little is known. A small group of these spheres, revolving about a central body, the star which we know as the sun, are better known, and together constitute the *solar system.* Omitting (*a*) occasional visitors to the solar system, or comets, (*b*) the small spheres or asteroids, (*c*) the still smaller meteorites, and (*d*) the rings of Saturn, there remain three quite distinct classes of bodies as constituent parts of the solar system: (1) the central sun, (2) the planets, (3) the satellites.

Similarities of Members of the Solar System. — Among the spheres that revolve about the sun, and especially the eight moderate-sized spheres called *planets*, there is a striking uniformity in some important respects. First and foremost, each has a spherical form. This is familiar in the case of the earth from the proofs in connection with (*a*) the circumnavigation of the globe, (*b*) the method of disappearance of ships upon the sea, and (*c*) the curved shadow of the earth during an eclipse of the moon (Fig. 2), as was well known to some of the ancients. Each planet is distorted by protuberance in the equatorial region into the form of an oblate spheroid.

FIG. 2. — Proof of the roundness of the earth from curved shadow during eclipse of moon. (Photograph by Harvard College Observatory.)

Secondly, all are *rotating* about an axis inclined to the plane through which they are *revolving* about the central body; but the inclination of the axis and the rate of rotation vary from sphere to sphere. In the third place, they are all engaged in a revolution about the central body, the sun, following an elliptical path, or *orbit;* while the satellites, in addition, are revolving about the planet to which they are attached. A fourth resemblance is that they all receive their light and heat from the central sun, though in amounts varying with the distance. Finally, it is probable, though not certainly proved, that all these spheres are composed of essentially the same materials.

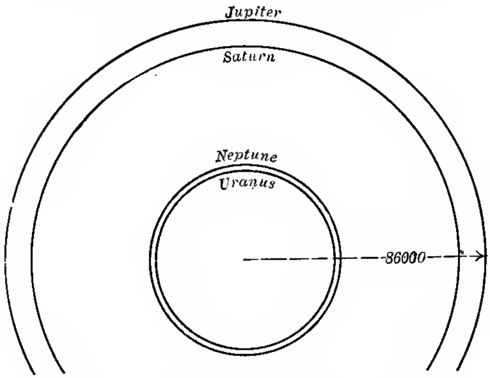


FIG. 3. — Relative sizes of the four larger planets.

Contrasts within the Solar System. — While there are these resemblances, there are also notable differences. The spheres differ greatly in size (Figs. 3, 4), ranging from the sun, with a diameter of 860,000 miles (Fig. 9), to the earth, with about $\frac{1}{100}$ this diameter, and the satellites with diameters of but two or three thousand miles, and to the still smaller asteroids. They differ also in their distance from the sun, and consequently in the length of the orbit through which they circle about it, as well as in the time required to complete the revolution (Fig. 5). Thus Mercury, the planet nearest the sun (Fig. 6), being approximately 36,000,000 miles distant, requires about 88 days for its journey about the sun; the earth, 92,750,000 miles distant, requires a little over 365 days, determining the length of our *year;* and Neptune, the most distant planet, 2,775,000,000 miles from the sun, requires about 165 years for its revolution.

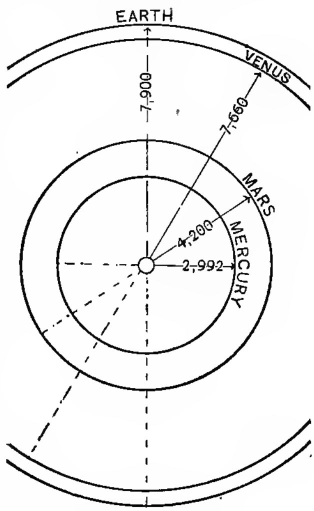


FIG. 4. — Sizes of the four smaller planets, given in diameters in miles.

A third noteworthy difference among the members of the solar system is the different periods of rotation, the earth turning on its axis in about 24 hours, and, therefore, determining the length of a *day,* while the sun rotates in 25 days, the moon in $27\frac{1}{3}$ days, and Jupiter in 9 hours and 55 minutes. That the earth does rotate from west to east upon its axis was long ago demonstrated by Galileo. In investigating the behaviour of objects falling through the air, he discovered that they always fell a little to the east of a point directly below that from which they were dropped (Fig. 7). At the Leaning Tower of Pisa, for example, the rotation of the earth causes an object at the top of the tower to move faster than one at its base, as Galileo correctly reasoned.

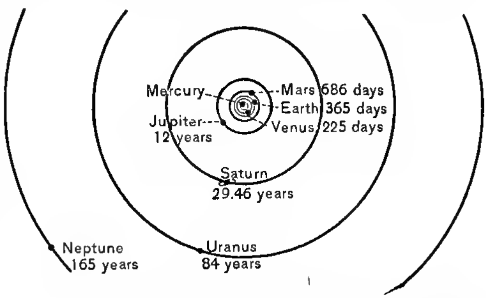


FIG. 5. — Diagram showing the time required for each planet to revolve around the sun.

The proof of the earth's rotation by *Foucault's pendulum* (Fig. 8) was first carried out in 1851 and is repeated every year in the physics or the geography departments of many

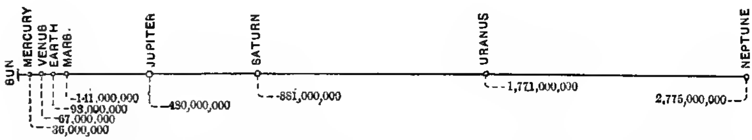


FIG. 6. — Diagram showing the distance from the sun to the various planets in miles.

colleges. Foucault's method was to suspend a heavy weight from the dome of the Pantheon in Paris, and set it to swinging. A pendulum will continue to swing indefinitely in exactly the same plane. After being set in motion it *appears* to cease to vibrate parallel to a mark on the floor, gradually comes to a position of swinging at right angles to the mark, and, in 24 hours or a little more, depending on the part of the earth, it seems to shift until it once more swings parallel to the mark. This is because the building turns around the pendulum as the earth rotates.

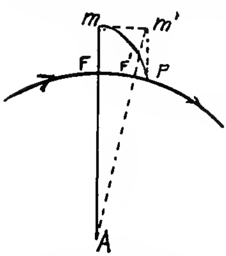


FIG. 7. — To show the deviation of falling bodies. (After Moulton.) An object dropped from the tower *MF* reaching the earth at *P* rather than at *F'*.

Still another contrast within the solar system is the condition of the spheres. On some, like the earth and Mars, there is an atmosphere, while on others, like the moon, there is no gaseous envelope. There seems also to be a gradation in temperature from the highly heated sun to the completely cold moon, with intermediate stages, such as Jupiter, which is evidently highly heated, though not glowing, and the earth, which, though cold at the surface, is apparently heated within.

While it does not fall within the province of Physical Geography to study the other members of the solar system, no presentation of this subject would be complete which ignored the resemblances and relationships which exist between the members of the great family of spheres which constitute the solar system. Nor would any attempt to understand the origin of the phenomena of the earth itself be fruitful without utilizing at least some of the facts which astronomers have contributed as a result of their study of the members of the solar system.

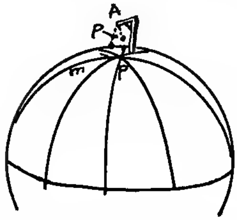


Fig. 8. — To show the relations of Foucault's pendulum to the rotating earth at the pole *P*, if it were started swinging in a plane parallel to the meridian *m*. (After Moulton.)

The Earth in the Solar System. — The earth is an integral part of this system; its movements in space are influenced and guided by its relation to other members of the great family of spheres; its light and heat, its tides, and winds and rains, together with the changes of the earth's surface, which result from their presence and action; and even the direct result of the astronomical relations of the earth and its history of development as a planet, — can be understood only by considering it as one of a series of spheres of common character and common origin.

Earth and Sun. — There is a difference in the degree of importance of the relationships between the earth and its fellow members of the solar system, and from the standpoint of the study of Physical Geography we may ignore all other relationships excepting those between the earth and the moon and the sun. To the sun the earth is bound by the tie of *gravitation*, which holds it to its elliptical orbit, as the moon is held to its orbit around the earth. Across the space of about 92¾ million miles, radiant energy passes from the sun, which shines in the heavens and like the other stars is fiery hot, to the surface of the earth, which merely reflects sunlight as the moon does. This radiant energy produces the phenomena of heat and light. Magnetic waves also span the distance, giving rise to phenomena upon the earth whose full significance is not yet understood.

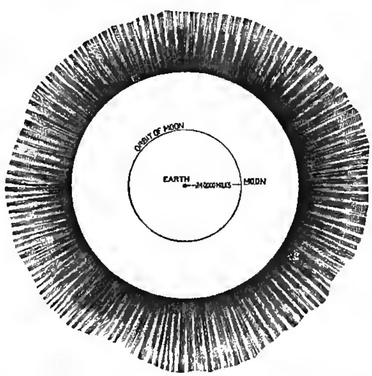
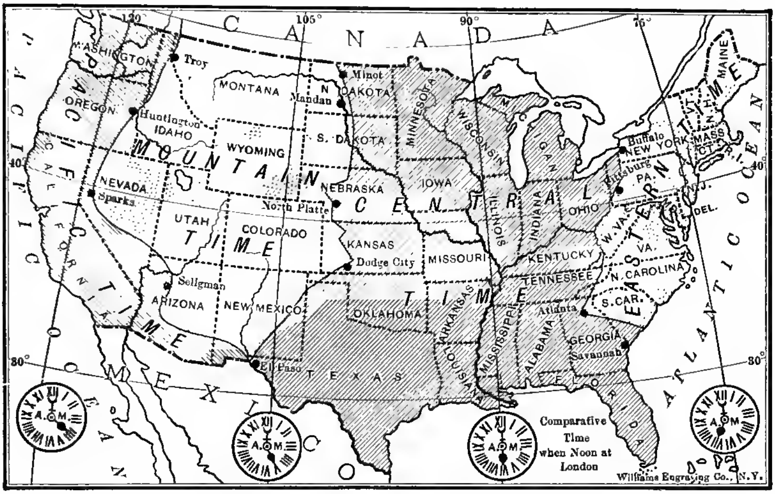


Fig. 9. — Diagram to show vast size of the sun compared with the earth. If the earth and moon and orbit of the moon were placed inside the sun, the relationship would still be as shown above.

By the inclination of the earth's axis to the *plane of the ecliptic*, the plane in which the earth moves in its revolution around the sun, the distribution of light and heat, which on a sphere would otherwise vary regularly from equator to pole, varies within other limits. These limits are constantly changing during the revolution of the earth about the sun; and, since the inclination is $23\frac{1}{2}°$ from the vertical, shift from a point $23\frac{1}{2}°$ north of the equator to a point $23\frac{1}{2}°$ south of the equator. Thus arise our *seasons* with all their momentous consequences.

Among the consequences of inclination is this. It happens that we have found it convenient to bisect the distance between the *North* and



STANDARD TIME IN THE UNITED STATES

FIG. 10. — The belts usually adopted in the United States.

South Poles, at the ends of the earth's axis, by an *equator*, and to subdivide it further along the line of *parallels of latitude*, among which the *Tropics of Capricorn and Cancer* and the *Arctic and Antarctic Circles* are definitely related to the inclination of the earth's axis.

Because of the period of daily rotation of the earth (23 hours and 56 minutes) the point upon which the sun's rays strike vertically is constantly and steadily shifting eastward, and thus in a day a line is traced around the earth upon which the sun's rays strike vertically, making it convenient, among other things, to have *meridians of longitude*, reckoned from the arbitrarily chosen *prime meridian* at Greenwich. The parallels and meridians are divided into degrees, and these are divided into minutes and seconds. A degree of longitude at the equator is about $69\frac{1}{2}$ miles; in the latitude of Philadelphia, Denver, Madrid, Peking, and New Zealand it is only about $53\frac{1}{2}$ miles; in the latitude of St. Petersburg it is about 35 miles; and at the poles it has

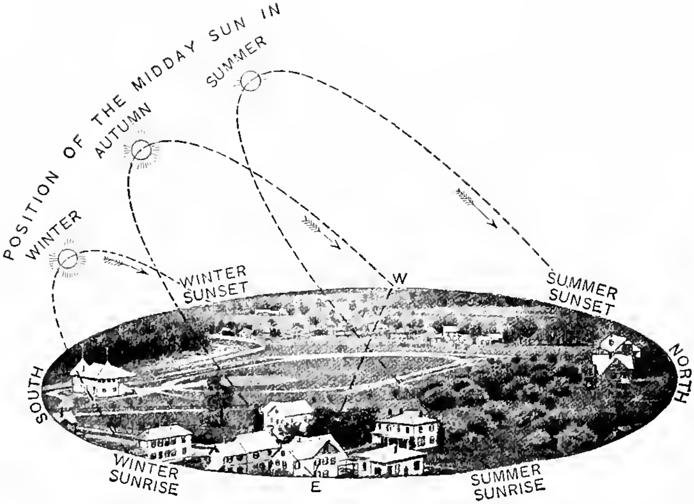


FIG. 11. — Diagram to show why the sun appears to rise farther north in summer than in winter. (From Todd's "New Astronomy.")

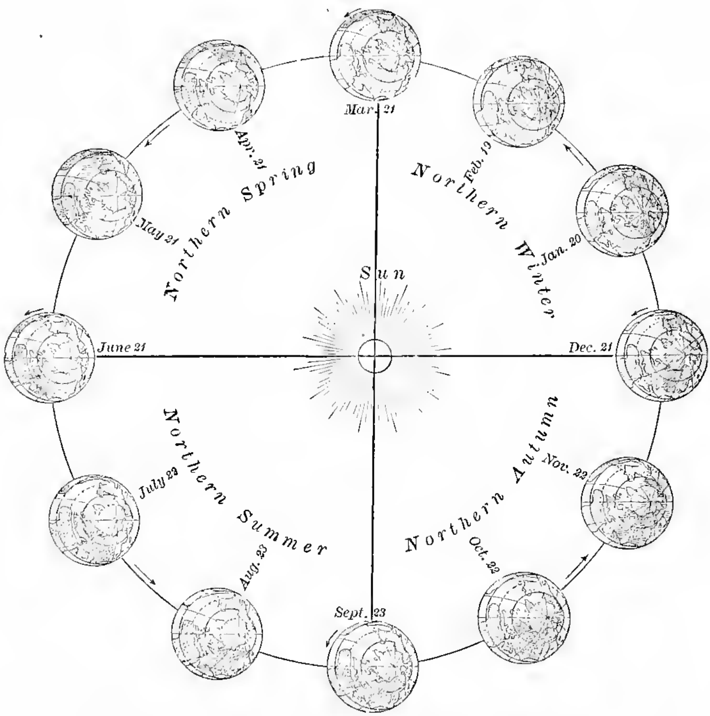


FIG. 12. — Diagram to show the portions of the earth illuminated at various seasons during revolution around the sun.

no length. A degree of latitude varies in length from 68.7 to 69.4 miles, because of the earth's polar flattening. As a result of the earth's daily rotation it is also necessary for us to have *Standard Time* (Fig. 10).

From the point of verticality of the sun's rays the angle at which the rays reach the earth is lower and lower in each direction. With the change of seasons (Fig. 12) the line of verticality shifts northward and southward, from the Tropic of Cancer on the north to the Tropic of Capricorn on the south. Accordingly the sun appears to rise farther north in summer in the northern hemisphere than in winter (Fig. 11). Likewise the polar regions are without light throughout the period of earth's rotation during parts of the year, and continuously lighted at other periods (Fig. 12) at all points within 23½° of the poles, that is, inside the Arctic and Antarctic Circles.

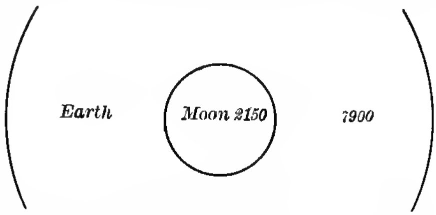


Fig. 13. — Diagram showing relative sizes of the earth and the moon, diameters in miles.

To day and night, and to seasons, with the resulting alternations of temperature and other conditions, are to be ascribed some of the most significant phenomena of Physical Geography, and some of the most momentous consequences to the surface of the earth and to life upon it.

Earth and Moon. — The moon, though near, is both small and cold. It gives to us only reflected light and a negligible quantity of heat. It is small (Fig. 13), but is very near the earth (average distance 240,000 miles, least possible distance 221,000, greatest 259,600 miles). Despite its smallness it nevertheless exerts an important effect upon the earth by the *attraction of gravitation*, most noticeable in the liquid part of the earth, the great oceanic envelope. Thrown into undulation by this attraction, the ocean surface rises and falls in tides which follow

Fig. 14. — Diagram to show positions of earth, *E*, and moon, *M*, during eclipses. (After Encyclopedia Britannica.)

the moon in its passage through the heavens. Though a far larger body, the sun, owing to its greater distance, is much less effective than the moon in tide generation, but a distinct solar tide is nevertheless produced, thus modifying the lunar tide. There are some reasons for believing that there are other influences of the moon with important consequences in the operation of physical forces on the earth, but the operation of these is so obscure that their full significance is not understood. Among these are the possible tide produced in the atmosphere and a possible relation between earthquakes and lunar attraction. In the revolution of the moon around the earth, and of the earth around the sun we have lunar and solar *eclipses* (Fig. 14) at certain times.

The Earth in Space

Importance of Uniform Conditions. — As a mere sphere of rock the earth might maintain its individuality and chief characteristics even though the conditions surrounding it were greatly changed; but as a body inhabited by a complex series of organisms, the earth is to be considered as dependent for its very existence as a habitable globe upon the maintenance of a balance in which there are a variety of factors. No one of these factors can be seriously disturbed without a complete alteration of the conditions upon which the existence of life depends.

Atmospheric Protection from the Cold of Space. — Passing rapidly through space, the earth is surrounded by such low temperatures that, if the supply of heat from the sun were cut off or greatly diminished, the temperature of the earth would quickly descend so low that life could not exist. Even a diminution in the atmospheric blanket would so upset the balance that, during the intervals of darkness, the earth, through radiation, would be exposed to the influence of the surrounding coldness. It is estimated that the temperature of space is but little (5° Centigrade) above that of absolute zero, or 459° below zero (Fahrenheit); the moon, on the side away from the sun, is under its influence; the earth is protected from it by its blanket of atmospheric gases, warmed by the sun during the earth's daily rotation.

Other Uniform Conditions. — The maintenance of daily rotation, and of an annual revolution, the preservation of favourable distance between earth and sun, and the continuation of a supply of heat from the sun, neither too great nor too little, are all factors upon which the earth as a habitable globe depends. The atmosphere, from which oxygen is being constantly extracted both by life and by inorganic processes of rock alteration, must maintain a supply sufficient to the needs of abundant life; and carbon dioxide, both extracted from the atmosphere and returned to it, cannot vary in quantity, excepting within narrow limits, without upsetting the balance. The distribution of land and water upon the earth, and the elevation of the land above the sea, are other factors, which, though capable of variation within limits, could not vary to an extreme, without giving rise to profound modification of the relation of life to the earth.

Habitability Long Maintained. — That at a given time the earth presents a set of conditions of complex kind, all conspiring to render it suitable as the home of a vast and complicated series of organisms, is perhaps not remarkable; but when it is considered that this favourable balance has been preserved through the long ages of the past with which geological study has made us familiar, through untold millions of years in fact, it is certainly noteworthy, to say the least. In the present we see the past reflected through the vista of the ages. But this is not the same as saying that the past has in no important way differed from the present. There is good reason for believing, and the evidence of it is steadily accumulating, that there have been periods in the past history of the earth when conditions were greatly different from the present; but through it all, so far as the facts now known permit us to judge, there has been no time when the steady development of life on the earth was interrupted, or even seriously jeopardized. This is certainly a wonderful fact, and one that may well set us to serious thinking upon the mysteries of nature by which we are surrounded.

The Earth Elements

Air, Water, and Earth. — The earth consists of three quite different parts: (1) the air or *atmosphere;* (2) the waters of the earth or *hydrosphere;* and (3) the solid earth, or *lithosphere.* Speaking generally, these parts of the earth are not only different but distinct from one another and fairly definitely separated. Yet it is not to be overlooked that both air and water penetrate into the solid earth; that water and solid earth enter the atmosphere; and that air and earthy materials find their way into the hydrosphere. There is, therefore, an intimate commingling of the three elements of the earth, though only within narrow limits and not enough to cause confusion in the attempt to distinguish them as definitely separate parts of the terrestrial sphere. It is not unreasonable to add still a fourth element, as some have proposed, — namely, the organisms of the earth, forming the *biosphere,* which occupies parts of the hydrosphere, the lower layers of the atmosphere, and the surface and outer portion of the lithosphere, and which depends upon the presence of these three elements for its existence. Physical Geography deals with a study of these four elements of the earth in their natural relation to one another and their reaction upon one another, under the influence of a series of forces from both within and without the earth, primarily radiant energy from the sun, and gravity in the earth itself.

The Atmosphere. — The atmosphere completely envelops the earth, rising certainly as much as 100 miles above the surface of the lithosphere, and perhaps as much as 200 miles, or even more. Because it is drawn to the earth's surface by the pull of gravity and compressed in its lower layers, fully half the air lies within about three and a half miles of the earth's surface, upon which it rests with a pressure of about 15 pounds to the square inch at sea level. Consisting of elastic gases which are readily set in motion by changes of temperature, the atmosphere is the theatre of incessant changes. In some of its activities the atmosphere exerts important influence upon the surface of the lithosphere and the hydrosphere; and it is vitally essential to the organisms of the earth. The composition of the air is also responsible for important consequences, especially through the influence of three of its constituents, — oxygen, carbon dioxide, and water vapour. Since these effects of the atmosphere are stated with some fulness on later pages (Chapters XXII to XXVII), their consideration may for the present be deferred.

The Hydrosphere. — The hydrosphere is only a partial envelope of the earth, by far the greater part of it being in the oceans. They cover nearly three fourths of the earth's surface to an average depth of about 12,000 feet, with a maximum depth near the Philippine Islands of 32,114 feet. Like the air, the oceans are the seat of incessant activities; and where they come in contact with the lands, at their borders, the effect of these activities is extended to a modification of the land itself.

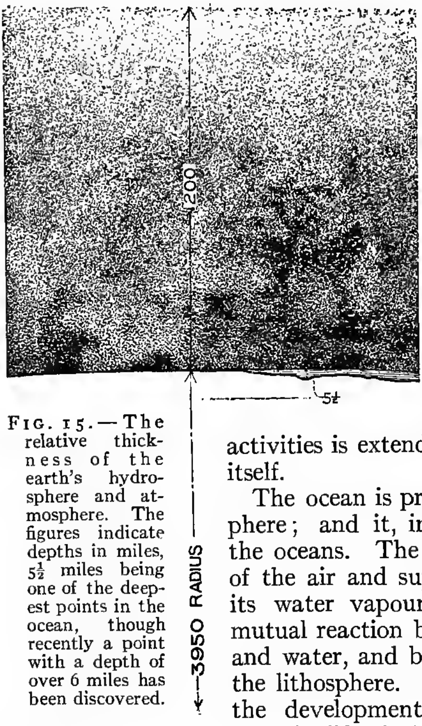


FIG. 15. — The relative thickness of the earth's hydrosphere and atmosphere. The figures indicate depths in miles, 5½ miles being one of the deepest points in the ocean, though recently a point with a depth of over 6 miles has been discovered.

The ocean is profoundly affected by the atmosphere; and it, in turn, is greatly influenced by the oceans. The ocean modifies the temperature of the air and supplies by far the greater part of its water vapour. Thus there is an intimate, mutual reaction between the two elements of air and water, and between these and the surface of the lithosphere. One important result of this is the development of a series of phenomena of fundamental importance in Physical Geography (Chapters XIX to XXI).

The Lithosphere. — By far the greater part of the earth sphere is the solid lithosphere, a body of rocky material with an equatorial diameter of 7926 (7926.5) miles, a polar diameter of 7900 (7899.7) miles, a circumference of about 25,000 miles, and a total volume of about 260,000,000 cubic miles. At the surface it consists of a complex series of rocks and minerals more or less completely oxidized, with an average specific gravity of 2.7, and with a temperature varying with the season. Fractures exist in this outer portion of the lithosphere, and, when stresses are applied, the consolidated rocks and minerals suffer breakage. This portion of the lithosphere is commonly known as the *earth's crust;* it has also received the name of the *zone of fracture.*

Heated Interior of Earth. — Those portions of the lithosphere which have come under the direct observation of man are in this zone, and no essential difference is noted between the deepest parts so far exposed and the surface, excepting a difference in temperature. Below the zone influenced by the seasonal changes the temperature of the earth's crust is found to rise with increasing depth; and while the rate of increase in temperature varies greatly from place to place, it is found to be on the average about 1° F. for about 50 feet of descent. From this it has long been inferred that the interior of the earth is highly heated, and if the observed rate continues, this conclusion is, of course, necessitated. That the earth's interior is in the state of a highly heated body has also been inferred from the condition of other members of the solar system — notably Jupiter and the sun, which are thought to have had a similar history to that of the earth, but not to have progressed so far in the state of cooling, while smaller bodies, like the moon, have gone even much farther than the earth. Still another basis for the inference of a highly heated interior is the fact that molten rock and hot waters emerge from within the earth at various points on the surface.

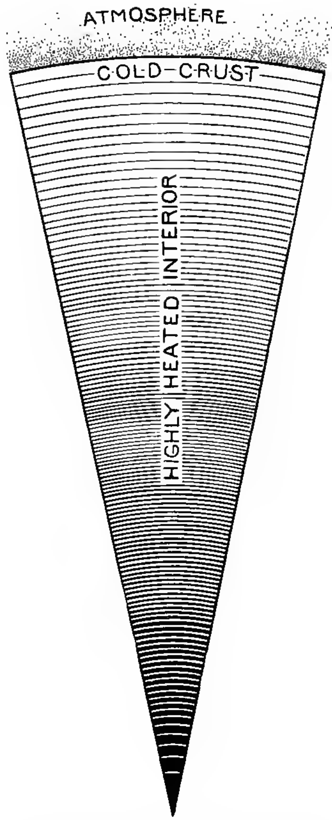


FIG. 16. — The relative thicknesses of the lithosphere and the atmosphere.

This conclusion has been controverted, and rival hypotheses have been put forward, a discussion of which will not be undertaken at present. Direct observation of the earth below the limit of a few thousand feet being prohibited, our knowledge of the interior is, of necessity, limited. That the interior is not a highly heated liquid, as once supposed, seems established now (*a*) by the evidence of the behaviour of the earth toward the moon and other members of the solar system, (*b*) by the absence of interior tides, and (*c*) by the nature and rate of movement of earthquake waves. It is apparently a solid mass, not very different from steel in specific gravity and rigidity, for while the average specific gravity of the crust is about 2.7, the specific gravity of the earth as a whole is about 5.66, and steel is about 7. It is even possible that the interior of the earth is unoxidized metal, for there are certain facts suggestive of this, notably the magnetic phenomena of the earth, and the composition of lavas which bring to the surface a larger proportion of metallic elements than is common in the minerals of the crust.

Flowage in Earth's Interior. — Of one characteristic of the hidden interior of the earth there seems good evidence,— namely, that, even though solid, and possibly cold, it nevertheless behaves as a viscous fluid when under stress. When under differential pressure, it yields and flows. This has long been suspected upon the basis of evidence that rocks, formerly deeply buried in mountain areas, but now revealed to view by erosion, have, under the stresses of mountain formation, moved by viscous flowage, instead of mechanical breaking such as the rocks of the surface are subject to. This has also been inferred upon the basis of theory, for under the heavy load of superincumbent layers, and especially if the temperature be high, mechanical breaking becomes an impossibility. The studies of the behaviour of metals under pressure, and more recently the brilliant experimental researches of Adams upon the effect of differential pressure upon various rocks under heavy load, have given to this theory satisfactory support. The conclusion seems, therefore, warranted that at a sufficient depth in the earth, all cavities become closed and fractures impossible, and that in that zone differential stress finds relief in rock flowage. To this part of the lithosphere, therefore, the name *zone of flowage* has been applied by Van Hise. It does not commence at a uniform and definite depth, but varies with the pressure and with the nature of the rock. It begins, in general, at depths of between 90,000 and 105,000 feet below the surface.

The Form of the Earth

The Oblate Spheroid. — The earth, in the largest sense, is a sphere, but, owing to rotation, it is distorted by flattening at the poles and spreading, or bulging, in the equatorial region, becoming therefore an *oblate spheroid.* As a result of this distortion of the sphere, the equatorial diameter is about 27 miles longer than the polar. While this is the greatest departure of the earth from the figure of a true sphere, it is by no means the only distortion. If the ocean, which tends to restore the oblate spheroidal form to the distorted earth, be ignored, and only the lithosphere be considered, the earth is found to depart so widely from the perfect form of an oblate spheroid, that it has been thought by some to deserve the special name of *geoid.*

Continents and Ocean Basins. — The greatest departures from the spheroidal form are those of the great continental elevations and oceanic depressions, the full extent of which is hidden from view by the ocean water which occupies the great depressions. The continents, which occupy about one-fourth of the total surface of the earth, rise to an average elevation of about 2300 feet above sea level, though in places reaching elevations of ten, fifteen, and twenty thousand feet, and culminating in Mount Everest with an elevation of 29,000 feet. The ocean basins, on the other hand, with an average depth below sea level of about 12,000 feet, have extensive areas with a depth much greater than this, and at their deepest point attain a depth of 32,114 feet, in which Mount Everest might be placed with a half mile of water over its summit. Since the mean surface of the lithosphere is about 7500 feet below sea level, it will be seen (Fig. 17) that a very large part of the surface of the earth falls below that limit, while the continents,

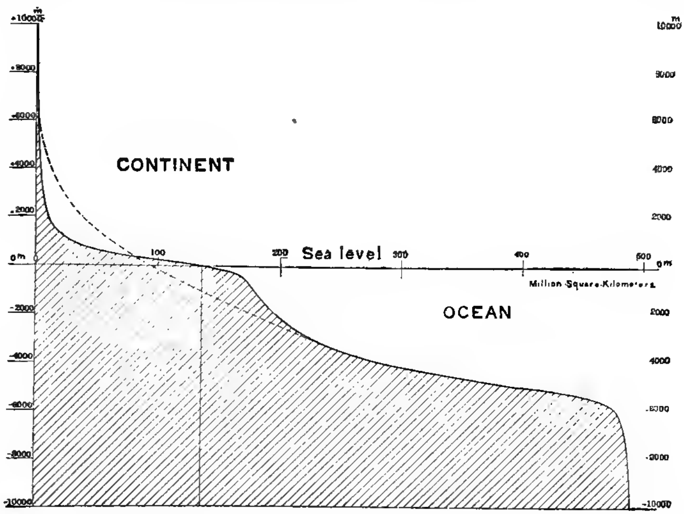


FIG. 17. — Relative proportions of land above and below sea level. Elevations in metres. Figures on horizontal lines in millions of square kilometres. (After Penck.)

together with some of the peripheral sea bottom, lie above it. How great and extensive are the oceanic depressions is indicated by the fact that if the lithosphere were perfectly spheroided, the waters now in the oceanic basins would overspread the entire earth with a hydrosphere nearly two miles in depth.

The diversity of the earth's surface due to the ocean basin depressions and continent elevations attains a maximum of over eleven miles, measured from the deepest known point in the ocean to the highest point on the land, the crest of Mount Everest; though the average difference between ocean basin depth and continent elevation is only about two and a half miles. The boundary between the continent elevations and the ocean depressions is commonly not at the line of contact between ocean and land, for the ocean overflows and floods the edges of the continents to a variable width. If, therefore, the oceans were removed, the extent and outlines of the continents would be materially modified; yet, in the main, they would retain their present figures, being extended, and modified in detail. Their borders would be the great, fairly steep slopes which now lie beneath the sea just outside the continent margins. On the land side of their slope the plains, hilly lands, and mountain ranges rise above the level of the

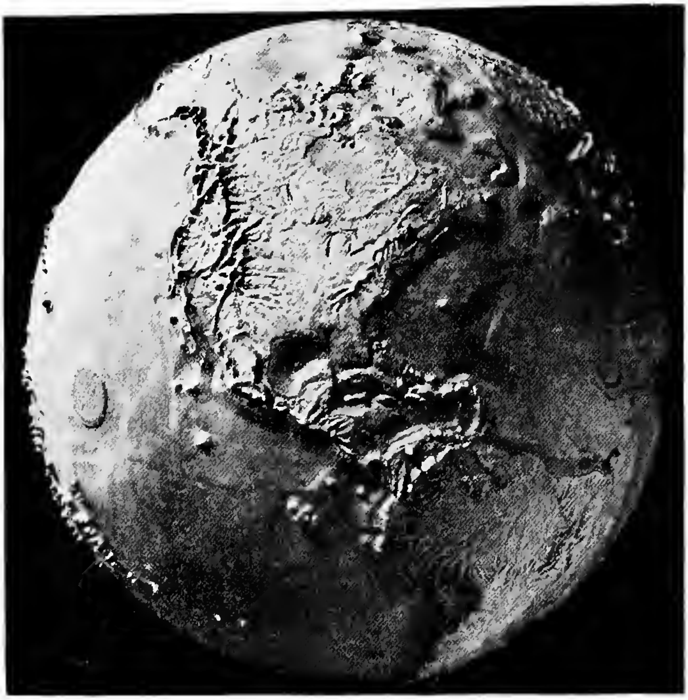


FIG. 18. — Model of the earth, showing the continents of North and South America in relief above the adjacent ocean basins. The real border of the continental plateau is beyond the coast, as on the Grand Banks east of Newfoundland. (Copyright, 1894, by Thomas Jones, Chicago.)

sea; on the ocean side there is a steep descent to the depth of the ocean with its broad expanse of ocean bottom plains.

Relief Features. — Both the continent elevations and the ocean basin depressions are diversified by irregularities of secondary rank. The dominant surface feature of the earth is the plain, both on the continents and in the ocean basins, but portions of the crust rise above these plains in linear bands, forming mountain ranges and chains. Although occupying but a small proportion of the earth's surface, these mountain uplifts give rise to great, though local, departures from the mean sphere level. In the opposite direction, still smaller portions of the earth's surface are depressed by the downsinking of limited areas, as in the depressions partly occupied by the Dead Sea and the depression in which the Mediterranean lies.

Still a third notable irregularity of the earth form is that which results from the repeated emission of molten rock from within the earth through an orifice of limited extent, giving rise to volcanic cones. These rise both from the sea floor and from the continents, mainly from near the continent borders, and usually along lines and in association with mountains. In some cases these volcanic cones, though occupying but a very limited proportion of the earth's surface, introduce a great departure from the spheroidal form, as, for example, in the Hawaiian Islands, a great volcanic mountain range rising fully 30 000 feet above the surrounding sea floor.

Erosion Features. — The earth's surface is still further diversified by a multitude of minor irregularities, especially in the lands, where the work of running water and other agencies of change have sculptured the surface into a complex series of forms, varying greatly in character and in magnitude. Most of these are so minute that, when compared to the earth as a whole, they are negligible; and even the greatest of the irregularities of the spheroid are but minute undulations on the surface of the great sphere, and exceedingly minor departures from the spheroidal form. Yet, when viewed from the standpoint of an occupant of the earth's surface, they stand out as great irregularities, impressive partly because of the limited range of vision.

Earth Activities

Conflict of Activities. — The irregularities of the earth's surface are the result of the operation and interaction of a series of processes at present actively at work, and active through a long distant past. The earth is the theatre of ceaseless activity and incessant change, and the departure of its form from that of a sphere is the result of the slow, long-continued operation of these activities. There are two sets of processes, in the main in conflict, one set inherent in the earth itself, the other derived from without the earth — hence one set *terrestrial*, the other *extra-terrestrial*, in origin. These processes, though in the main separable, are so completely interrelated in origin, activity, and resulting modification of the earth's surface, that it is only in the most general sense that they may be put apart.

Terrestrial Forces. — Inherent in the earth is the great force of gravity, tending to hold all objects in appropriate relation as inherent parts of a sphere, arranged according to specific gravity. Thus we have the three layers of (*a*) air, (*b*) water, and (*c*) rock, and, in the lithosphere itself, a lighter crust upon a denser interior. To a certain degree opposed to the operation of gravity is the centrifugal force introduced by rotation, as a result of which the earth has been given its greatest departure from the form of the true sphere, that equatorial bulging which makes it an oblate spheroid.

Because of conditions within the earth, the exact nature of which is not yet understood, still further diversity is given to the surface form of the lithosphere. Over large areas the crust is depressed below the main sphere level, while elsewhere portions rise above it, and the outline and elevation of these areas are even now undergoing change, as they have throughout past ages. Here and there the continent margins are rising, or are sinking, and a study of the past history of the earth proves that these variations have been in progress throughout geological time. Parts of the surface of the lithosphere have been thrown into great undulations along relatively narrow bands, as a result of which portions of the surface have been pushed high above the surrounding levels as mountain ranges and chains. These changes are even now in progress in certain parts of the earth, as they have been during the geological ages. Likewise, now, as in the past, molten rock is being extruded to form local elevations in parts of the lithosphere surface.

The great result of the operation of these terrestrial activities has been to give to the surface of the lithosphere the greatly diversified outline already mentioned; and, with the exception of the oblate form, the tendency of time has been to add to the diversification.

Extra-terrestrial Forces. — At all times there have been opposed to the tendency to produce diversification the operation of a series of activities whose main source of energy is derived from outside the earth, aided, however, by the force of gravity, by rotation of the earth, by revolution, and by the presence of air and water envelopes upon the lithosphere. Radiant energy from the sun is the chief of the extra-terrestrial forces, which, under various modified forms, becomes an agent of vast change in the lithosphere. It induces rock disintegration, and modifies and aids the work of the atmosphere in the same directions; it sets the atmosphere in motion, and either directly or indirectly through the atmosphere it sets up motions in the ocean also, giving rise to winds in the atmosphere, and to waves and currents in the ocean, all processes operating to modify the surface of the lithosphere; it aids in the introduction of vapour into the air, and by the winds which it generates it guides the distribution of this vapour, and in important ways, also, it helps to determine the fall of the vapour upon the earth, where, gathering into rills and rivers, it runs away under the pull of gravity, causing great modifications of the surface of the earth when operating through long periods of time; it is one of the vital factors upon which life on the earth depends, and life is in various directions one of the agencies of change in the surface of the lithosphere.

Gravitation, operating to hold the members of the solar system in their place, and to keep the earth and moon in their paths of revolution, is to be reckoned as another highly important extra-terrestrial force, upon which depend many of the activities of the earth resulting from the influence of radiant energy. A more direct effect of gravitation is the disturbance of the ocean by the tidal waves which twice each day sweep over its surface, performing much work in modifying the surface of the lithosphere, especially along the continent margins.

Balanced Result of Upbuilding and Tearing Down. — In a general sense the forces from within the earth, and those derived from outside, may be considered to be in some important respects in opposition, or conflict. Those operating from within the earth are tending toward diversity of surface form, those from outside the earth, coöperating with gravity and utilizing the air and water as agencies, are tending toward reduction of irregularities, tearing down the higher portions here and building up the depressions. Were the terrestrial activities to operate unchecked, the surface of the lithosphere would attain a far more striking degree of irregularity than now, as is the case on the surface of the moon; were internal activities to cease, while those generated from without the earth continued, the earth's surface would diminish in irregularity. With both sets of activities in operation, there is a double cause for irregularity, for those diversities introduced by the terrestrial activities are only partly removed, and they bear the scars of the attacks made upon them by the activities whose main source of power is sent across space to the earth. The battered and scarred surface of the earth, bearing the marks of the conflict and interaction of terrestrial and extra-terrestrial activities, is the subject of the study of the physical geography of the lands. The processes are still in operation all about us, and the results which they have produced during the ages that are past, are to be understood and interpreted only through a knowledge of the nature of the activities at present in operation.

Another Classification of Activities. — The processes by which the surface of the earth has been given its present shape in departure from that of a perfect oblate spheroid may be grouped in another way into three divisions, *diastrophism*, *vulcanism*, and *denudation.*

Diastrophism deals with the nature and effects of movements of the crust by which some parts are raised and others lowered in relation to one another. *Vulcanism* deals with the nature and results of the movements of molten rocks from one part of the earth to another, and, from the standpoint of physical geography, primarily a movement from some point within the earth to the surface of the lithosphere. *Denudation* includes the operation and results of a complex series of processes by which the surface of the lithosphere is attacked — it is the expression of the tendency to lower the level of the lithosphere to the perfect spheroidal form by removing those parts that are too high and filling those parts that are too low. Because diversities are ever being added, the work of denudation, though in operation during the millions of years of geological time, accomplishing vast results, has failed to even approximate the ultimate end toward which gravity is tending to lead it.

Denudation. — Under denudation is included two quite different classes of processes (1) *weathering*, or rock disintegration, (2) *erosion*, or rock removal and transportation. The former tends to prepare the rock for the more efficient work of the latter. Erosion and weathering each operate both by mechanical and chemical means, and in some of these phases they are aided by organic processes, while throughout they are dominantly influenced by gravity. Weathering, *per se*, goes no further than the disintegration of rock, though by the aid of life, of gravity, or of wind and water, the weathered rock products may be moved from their place of origin to a place of deposit. Erosion, on the other hand, involves three stages: (*a*) removal, (*b*) transportation, and (*c*) deposition of rock fragments, or *degradation*, *transportation*, and *aggradation*.

The agencies of erosion are several, as follows: (*a*) gravity, (*b*) organisms, (*c*) air movements, (*d*) running water, (*e*) glaciers, (*f*) waves, tides, and currents in lake and ocean. The operation of the agencies of erosion and weathering are more or less intimately interrelated in the general work of the denudation of the land, and it is only for the purpose of clearness of presentation that it is warranted to separate them and treat them independently.

The nature and results of diastrophism and vulcanism are treated in later sections, after the study of the processes and effects of denudation. Though complex in their interaction, the agencies of denudation treated independently, and as if they were actually working separately, offer a simpler beginning in a study of the physical geography of the lithosphere than vulcanism and diastrophism; and, moreover, they are the processes with which we may begin with a better basis of acquaintance, since they are in operation round about us and in some of their phases are more or less familiar to the observant student. The agencies of denudation are actively at work, in one form or another, on all parts of that portion of the lithosphere which rises above the oceans, and to some, though variable, degree in the ocean basins also, at points away from the coast lines, however, mainly by deposition. The work of denudation is by no means uniform, being influenced by a great variety of conditions, such as slope, climate, and the composition, structure, and attitude of the rocks which are being attacked. Before considering the agencies of denudation in detail, therefore, it is necessary to gain a general view of the manner in which the rocks of the earth's crust vary.

The Rocks of the Earth's Crust

The Nature of Minerals and Rocks. — The chemical elements, sometimes singly, as in native copper or in sulphur, sometimes in combination, as in the silicon and oxygen which make quartz, occur in the earth's crust as *minerals*. The elements silicon, oxygen, aluminum, and potassium make up one variety of the mineral feldspar. A mineral may be defined as a single element, or two or more elements chemically combined, forming a part of the earth's crust.

The most common rock-forming minerals and their composition are listed in the following table.

TABLE SHOWING ROCK-FORMING AND OTHER COMMON MINERALS

THE MINERALS AND THEIR COMPOSITION

Quartz (SiO_2) (Silicon, Oxygen)	*Calcite* ($CaCO_3$) (Calcium, Carbon, Oxygen)
Orthoclase Feldspar ($KAlSi_3O_8$) (Potassium, Aluminum, Silicon, Oxygen)	*Dolomite* [$CaMg(CO_3)_2$] (Calcium, Magnesium, Carbon, Oxygen)
Plagioclase Feldspar [($NaAlSi_3O_8$) + ($CaAl_2Si_2O_8$)] (Sodium, Aluminum, Silicon, Oxygen, Calcium)	*Salt* (NaCl) Sodium, Chlorine)
	Gypsum ($CaSO_4$, 2 H_2O) (Calcium, Sulphur, Oxygen, Hydrogen)
Muscovite Mica [$H_2(K)Al_3(SiO_4)_3$] (Hydrogen, Potassium, Aluminum, Silicon, Oxygen)	*Pyrite* (FeS_2) (Iron, Sulphur)
	Magnetite (Fe_3O_4) (Iron, Oxygen)
Biotite Mica [$(H{\cdot}K)_2(Mg{\cdot}Fe)_2Al_2(SiO_4)_3$] (Hydrogen, Potassium, Magnesium, Iron, Aluminum, Silicon, Oxygen)	*Hematite* (Fe_2O_3) (Iron, Oxygen)
Hornblende [$(Ca(Mg{\cdot}Fe)_3(SiO_3)_4{\cdot}Al_2O_3)$] (Calcium, Magnesium, Iron, Silicon, Oxygen, Aluminum)	*Limonite* (2 Fe_2O_3, 3 H_2O) (Iron, Oxygen, Hydrogen)
	Siderite ($FeCO_3$) (Iron, Carbon, Oxygen)
Augite [$(CaMgFe)O(AlFe)_2O_3\,4(SiO_2)$] (Calcium, Magnesium, Iron, Oxygen, Aluminum, Silicon)	*Kaolin* [$H_4Al_2Si_2O_9$] (Hydrogen, Aluminum, Silicon, Oxygen)

These minerals are identified in a general way by various features of (*a*) colour, (*b*) lustre, (*c*) hardness, (*d*) number and arrangement of crystal faces, (*e*) cleavage faces and their directions, (*f*) fracture, (*g*) solubility in water and various acids, and (*h*) associations in rocks. They may be determined with greater refinement (*a*) by specific gravity, (*b*) by relation to heating tests under the blowpipe and in the presence of various chemical reagents, or (*c*) by grinding rocks to a thin section in which the constituent minerals may be determined under the high-power microscope by certain significant phenomena, including their behaviour with regard to the light passing through them under various conditions.

Quartz. — Quartz, or silica, forms the most common mineral in rocks and soils of the earth. Although slightly soluble in underground water, quartz does not decay, because its silicon and oxygen are so firmly united. The minerals opal, chalcedony, agate, and jasper are impure varieties of silica, as is the rock *flint*, or *chert*. Crystalline quartz occurs in six-sided prisms terminated by six-sided pyramids, but not all quartz is crystalline. Its lustre gives it a glassy appearance and its colours vary from clear to milky white, blue, rose, red, and variegated. It cannot be scratched with a knife, and although hard enough to scratch glass, it is brittle and, when broken, has a conchoidal fracture.

The Feldspars. — These minerals, which are *silicates* and therefore include silica in their composition, are among the most common substances in the earth, occurring in all the main classes of rocks. Feldspar is nearly as hard as quartz, and is not soluble, as quartz is, but is less durable. It decays when exposed to air and water, and in the course of time crumbles to *kaolin*, a dull, whitish clay. Decayed feldspar is common in many soils and is the source of the best pottery clay. *Bauxite*, a form of kaolin, is the source of aluminum. *Orthoclase* and *plagioclase* feldspar differ in that the latter has the elements sodium and calcium instead of potassium. There are still other feldspars.

In none of the feldspars are crystals common, but cleavage planes are conspicuous, extending through the feldspar, causing it to break along smooth faces, and facilitating its decay. Many feldspars are light-coloured.

The Micas. — The colourless variety of mica is familiar in the " isinglass " of stove doors, splitting into thin sheets because of its exceptional cleavage. It is the *muscovite* mica which is transparent, and this is because it lacks the iron and magnesium of the dark *biotite* mica. All micas are easily scratched with a knife and some of them decay rapidly, while others persist after the rocks in which they originally occurred are destroyed, appearing as shiny flakes in soils and in such rocks as shale and sandstone.

Hornblende and Augite. — Hornblende, as the table indicates, is of complex chemical composition. It is hard, black, lustrous, often crystalline; and with well-defined cleavage. It decays upon exposure to air and water, often staining the rock because one of its important elements is iron.

Augite is difficult to distinguish from hornblende, especially in small particles. It is usually green rather than black, its cleavage faces meet at a different angle, and its crystal form is different from hornblende. It also decays readily.

Calcite and Dolomite. — These *carbonate* minerals are alike in being easily scratched by a knife and in having cleavage in three directions, so that they break into readily recognized rhombs. Calcite, like quartz, is of variable light colours. It may be distinguished from quartz by its softness and by its solubility, which permits it to effervesce freely in acid. It is one of the most soluble of common minerals, and its cleavage planes allow water to enter and dissolve it, if carbon dioxide is also present. Thus a rock containing calcite is much less durable than one made up of feldspar and quartz. Calcite has pearly lustre and often has perfect crystals.

To the calcium of calcite (carbonate of lime), magnesium is often added, forming dolomite, which is less soluble. If the calcium is replaced by iron, then the heavy mineral *siderite* is formed, the brown "spathic" iron ore.

Salt and Gypsum. — Crystals of rock salt are most easily identified by their saline taste. They are cubes, and the cleavage is also cubical. The mineral is soluble in ordinary water and soft enough to be scratched by the finger nail, but not as easily as gypsum.

Like calcite, gypsum is a common constituent of "hard" water because of its solubility. It is often white, sometimes crystalline, splits into thin flakes because of perfect cleavage, but these flakes are not elastic as in mica. Salt and gypsum may also be regarded as rocks composed of a single mineral.

Iron and Iron Ores. — More common and valuable than siderite are the ferruginous minerals, *magnetite*, *hematite*, and *limonite*. The former may be identified by the fact that a magnet will pick up particles of it. It is heavy, usually crystalline, and of a metallic lustre. Hematite is heavy and may be red. It is sometimes crystalline (*specular iron ore*), sometimes earthy, and sometimes in smooth, rounded masses. Limonite is yellow. The common iron rust is limonite, which also occurs sometimes as an ore, one variety being *bog iron ore*. Hematite is the most important of the iron ores, supplying nine-tenths of the iron produced in United States. Limonite gives a yellow streak, hematite red, and magnetite black when scratched on a piece of china or on white quartz.

Iron pyrite is not an iron ore, though sometimes a source of sulphuric acid. When copper is added (*chalcopyrite*), this is often a valuable copper ore. Gold also occurs in pyrite, though very rarely, but pyrite is often mistaken for it and hence is called "fool's gold." This resemblance is striking, because pyrite is a heavy, golden-yellow mineral. They may be distinguished because of the hardness of pyrite and the softness of gold, which is easily scratched with a knife. Pyrite often has cubical crystals.

Since small quantities of iron are present in a great number of minerals and rocks, and since the oxidation or rusting of the iron goes on rapidly, a red stain is given to many rocks and many soils are red with hematite stain or yellow with limonite stain.

Minerals in Rocks. — The common rocks, which will now be discussed, are constituted chiefly of the dozen or so minerals listed above (see tables, pp. 24, 26, and 28). Only one or two hundred of the 2000 or more known minerals are abundant. Locally the others may occur in considerable amounts, but all except the common and rock-forming minerals are relatively rare in the rocks of the earth. Some of these rare minerals, for example, the gems, the ores of gold, silver, copper, lead, zinc, tin, platinum, and the ore containing radium, are highly prized by mankind. A *rock* is an aggregate of minerals, sometimes chiefly or entirely of a single mineral species, as in the case of rock salt, ice, and some limestones, but more commonly of two or more different minerals. In common usage a rock is something hard, but in the geological usage hardness and consolidation are not necessary characteristics of a rock. Thus sand is as certainly a rock as is a sandstone used in building; and there is every gradation in the earth's crust between the loose sand, and the sand which, through deposit of a

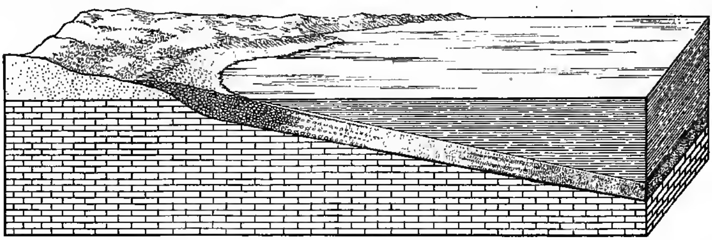


FIG. 19. — The gradation in sedimentary rocks in the sea from pebbles near shore, to sand in deeper water, and clay still farther from the coast. A similar gradation and intercalation takes place in sedimentary rocks deposited on the land by rivers.

mineral cement, such as silica, calcite, or iron, has the grains bound together to make the sandstone. In a similar way, the line cannot be drawn between the liquid rock which flows as lava from a volcano and the solidified lava on the slopes of the volcano.

Kinds of Rocks. — In the crust of the earth there are a multitude of minerals, and these have been assembled in a multitude of ways, giving rise to a great variety of rock species and varieties. Three great groups of rocks are commonly recognized, on the basis of their origin: (1) *sedimentary* rocks, (2) *igneous* rocks, (3) *metamorphic* rocks. The members of one of these rock groups differ from those of either of the other groups in significant respects; and the members of a single group differ from one another in more or less notable ways. The full study of these differences forms the science of petrology, but physical geography is concerned with some of the more significant differences.

Sedimentary Rocks. — The most widespread of the rocks are those that have been accumulated from the disintegration, transportation, and deposition of previously existing rocks. The principal agents of such transportation are air and water, — the latter operating in the form of rivers, lakes, oceans, and glaciers. During the transportation of the rock fragments there is a more or less perfect assortment of the fragments according to their specific gravity, or weight, and the transporting power of the agent of transportation; and in their deposition there is an arrangement, more or less perfect, according to the size of the particles. Thus, there are deposits of pebbles, of sand, and clay, and as the supply varies, or the transporting power varies, these layers may alternate one above the other (Fig. 19). This assortment, and the resulting deposit of layers, gives rise to *stratification*, which is such a characteristic feature of sedimentary rocks, that they are often called *stratified rocks*. The layers, or *strata*, vary greatly in kind and in thickness, sometimes occurring in massive strata having great thickness and uniformity, at other times in thin layers with rapid alternations from one kind of rock to another.

Fig. 20. — A fossil leaf from the coal beds of the Carboniferous, showing that there may be plant as well as animal fossils, and terrestrial as well as marine sediments.

Although derived from the waste of previously existing rocks, and originally deposited in unconsolidated state, the sedimentary layers are commonly changed to the consolidated state, primarily by the deposit of mineral matter which acts as a cement to hold the individual grains together. Thus beds of pebbles are changed to *conglomerate;* sand to *sandstone*, and clay to *clay rock* and *shale*. Such rocks, consisting as they do of fragments derived from the waste of other rocks, are often called *fragmental*, or *clastic* rocks. There are two other ways in which rocks of this class may be formed, the first by deposit from solution, as in the case of rock salt, the second by the work of organisms, both plant and animal. Plant remains, for instance, give rise to *coal* strata; petroleum and natural gas, which of course are not rocks, though found in sedimentary strata, are complex compounds of carbon and hydrogen whose origin is not fully understood, though of great value to man; the shells and limey parts of various animals, notably shell-fish and corals, cause deposits of *limestone*, one of the most common and widespread of the sedimentary strata, also thought to be sometimes formed by direct precipitation of lime in the ocean. *Cement rock* and some *phosphate rock* are also marine sedimentary rocks, though the latter is afterwards altered. A magnesian limestone is called *dolomite.*

Both the clastic rocks and the limestones of organic origin are now being accumulated mainly in the oceans; and the same has been true of those rocks formed in the earlier geological ages, as is proved by the presence of *marine fossils* entombed in them. That the most widespread rocks of the lands are the sedimentary strata, and that the greater portion of these were deposited in the oceans, testifies to the fact, otherwise abundantly proved, that the relative position of land and sea have undergone great change in the past. There are also *terrestrial deposits,* their fossils being non-marine (Fig. 20).

SEDIMENTARY ROCKS

Origin	Name	Composition
Fragmental, or clastic rocks.	Gravel beds. Conglomerates. Sand beds. Sandstones Clay beds. Shale.	Made of pebbles derived from other rocks. Consolidated masses of pebbles. Finer fragments, usually quartz grains. Consolidated sand beds. Disintegrated feldspar, hornblende, etc. Consolidated clay beds, splitting readily.
Chemically formed rocks.	Stalactite, oolite, calcareous tufa. Iron deposits. Silicious sinter. Salt. Gypsum.	Carbonate of lime, deposited in water. Some ores of iron, especially bog iron ore. Silica deposited from water. Sodium chloride. Sulphate of lime.
Organic rocks.	Most limestones. Dolomite Coal (bituminous, lignite, peat).	Carbonate of lime, made of shells, etc. Magnesian carbonate of lime. Made of plant remains.

Igneous Rocks. — The igneous rocks have all been in a melted state, having been forced upward from within the earth (Fig. 22), and, on cooling, solidified in the position where they are now found. The igneous rocks differ from the sedimentary rocks in the general absence of assortment and stratification and in being made up of interlocking mineral grains clinging together, not by the deposit of a cement, but by consolidation on changing from the liquid to the solid state. The latter quality gives to them a crystalline structure (Fig. 21) — being made of an aggregate of crystals; the former gives them a massive structure as distinguished from the stratified structure of the sedimentary rocks.

The differences among the igneous rocks themselves are numerous, and are due primarily to two quite different causes. The first of these is the difference in the kind of mineral of which the rocks are made, and on this basis many different species of igneous rocks have been recognized. The chief underlying reason for these differences is the chemical composition of the lava from which the igneous rocks are made, and this varies from one part of the earth to another.

A second difference among igneous rocks is dependent upon the position in the earth's crust in which the lava cooled. In volcanic regions the lava is expelled into the air, where it cools; but lava has also risen toward the surface, without actually reaching it. That which reaches the air cools quickly, and the minerals of which it is composed do not have time to grow to the size that is possible in those buried masses which, protected by a blanket of overlying rocks, require a much longer time for cooling and solidification. Thus, lavas that flow out at the surface are dominantly finer grained than those intruded into the strata, and later revealed by the wearing away of the overlying layers.

Fig. 21. — A specimen of diabase, a fine-grained igneous rock, enlarged to show the interlocking crystals of feldspar and augite. Some trap rock is diabase.

Granite (Fig. 23) is one of the most common of the intruded rocks, thrust into the strata in great masses, sometimes called *bosses* (Fig. 22); but there are other intruded rocks, some in bosses, others in *sheets* between the layers, some in *dikes* which cut across the layers, and some in other forms of intrusion. There are also numerous kinds of lava, one of the most common of which is *basalt*. Besides varying in mineral composition, lava differs much in texture, some, like *obsidian*, being so fine grained as to form a natural glass, others with sufficiently coarse grain for the individual minerals to be recognized. There is also a difference according to the effect of the expansion of steam included in the lava at the time of its emission. In some cases the expansion of the included water blows the lava to bits, making a volcanic ash which, drifted by the wind, may settle on land or water and build up layers of stratified rock. In other cases the lava is blown so full of holes by the expanding steam, that the solidified lava is porous, and even spongy in texture, as in the case of *pumice* (Fig. 23).

Igneous rocks are dominant in the neighbourhood of active volcanoes, as would be expected; but they are also found, often over wide areas, as in western United States, where volcanic action is no longer present. This proves clearly that vulcanism has in previous ages been present in areas now free from it. For example, the Rhine valley crosses a region of former volcanic activity; northern Ireland and western Scotland, as well as other parts of the British Isles, have witnessed great volcanic outflow and intrusion; and the Palisades of the Hudson, in the very suburbs of New York City, are made of lava. Furthermore, as the surface of the land is slowly wasted by denuda-

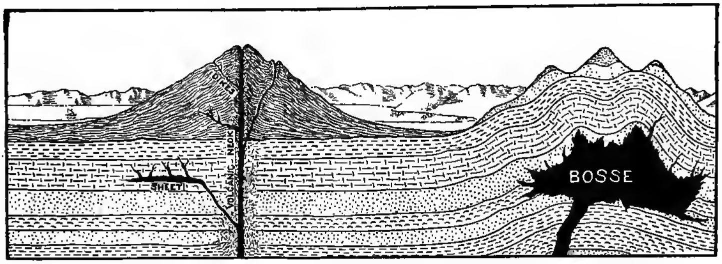


Fig. 22.—Variable conditions of deposit of igneous rock as in the volcano on the left with its dikes, sheets, and ash deposits, and the bosse on the right where the molten rock cools deep below the earth's surface.

tion, it is not uncommonly the case that in or beneath the sedimentary strata volcanic intrusions are revealed that were thrust into the strata in bygone ages, and often in places where no other sign of volcanic action has been discovered. All these igneous rocks, both extruded and intruded, slowly crumble when exposed to the air, as other rocks do, and supply materials for the formation of clastic rocks.

IGNEOUS ROCKS

Texture	Name	Chief Mineral Components
Coarse grained	Granite.	Quartz, feldspar (orthoclase), and hornblende, or mica, or both.
	Syenite.	Feldspar (orthoclase) and either mica, or hornblende, or both.
	Diorite.	Feldspar (plagioclase) and either hornblende, or mica, or both.
Either coarse or fine grained	Diabase.	Feldspar (plagioclase) and augite.
Fine grained.	Rhyolite (quartz porphyry).	Quartz, feldspar (orthoclase), and hornblende, or mica, or both.
	Trachyte.	Feldspar (orthoclase), and either hornblende, or mica, or both.
	Andesite.	Feldspar (plagioclase), and either hornblende, mica, augite, or two of these.
	Basalt.	Feldspar (plagioclase) and augite (often still other minerals).

Metamorphic Rocks. — The third class of rocks, the metamorphic, as the name indicates, are derived from alteration, or metamorphism, of other rocks, whether igneous or sedimentary. In a sense, it is metamorphism when clastic fragments are cemented to form a solid layer of sedimentary rock; but this is not what is commonly meant by metamorphism. The continued action of water, especially if heated, may so alter a rock as to quite completely change its character, and it

FIG. 23. — The banded appearance of gneiss (on the right), in contrast with granite (on the left) and pumice (above).

then becomes a metamorphic rock. But more commonly it is heat and pressure, such as accompanies mountain folding, that introduces those extensive changes by which the metamorphic rocks are formed. Then sandstone may become so compact as to resemble massive quartz, forming the metamorphic rock, *quartzite;* or clay rocks may become *slate;* or limestone be altered to crystalline *marble.* Even further alteration may so transform a rock as to completely destroy the original characteristics, so that it is impossible to tell what the original rock was, or even to determine whether it was an igneous or a sedimentary rock before subjected to metamorphism. Such highly transformed rocks are of many different types, but for our purposes they may be considered as either *schist* or *gneiss*. The schist rocks are laminated, with a structure resembling stratification; but differing from stratified rocks in the absence of the clastic structure, and the possession, in its stead, of a crystalline structure resembling in certain respects that of the igneous rocks. Gneiss (Fig. 23) is far more massive, and in significant ways resembles granite, having a coarsely crystalline, massive structure, and often having the same minerals as granite. It differs from granite in the possession of a more or less perfect banding of the minerals, roughly simulating stratification.

The metamorphic rocks are, in the main, confined to mountain regions, and are, therefore, less widely distributed than the sedimentary strata. Having been formed in mountains, and deep beneath the surface, where pressure and heat were sufficient for their transformation, they are found at the surface only where the upper layers have been stripped off by denudation. But metamorphic rocks abound in areas, like much of eastern Canada and New England, which are not commonly recognized as mountains. Their presence in such places, together with other evidences, proves that these sections were in former ages the seat of extensive mountain uplift and folding now quite extinct. These old mountain regions, long exposed to denudation, and worn to their very roots, reveal the deep-seated strata which were changed, far below the surface, by heat and pressure during the extensive mountain folding of early geological periods. Thus metamorphic as well as igneous and sedimentary rocks testify to the mighty changes that have been in progress in the lithosphere during the long periods of the geological past.

METAMORPHIC ROCKS

Name	Source	Mineral Composition
Quartzite.	Altered sandstone.	Quartz.
Slate (argillite).	Altered clay rock.	Partially crystallized micaceous minerals developed out of the clay particles.
Marble	Altered limestone.	Calcite.
Anthracite (graphite).	Altered coal.	Mainly carbon and carbon compounds.
Schist.	Altered from various rocks, *e.g.* shale, conglomerate, diorite, etc.	Variable — usually two or more of the following: feldspar, quartz, hornblende, or mica.
Gneiss.	Altered from various rocks, *e.g.* shale, conglomerate, granite, diorite, etc.	Variable — usually two or more of the following: feldspar, quartz, hornblende, or mica.

Rock Structure and Position. — It is in their power of resistance to the attacks of denudation that rocks are of prime interest to the student of physical geography. In this respect there is much difference among rocks, due to a variety of conditions. There is, in the first place, a great variation in hardness from the soft, unconsolidated clays and sands on the one hand to the massive quartzite, so hard that it cannot be scratched by steel, on the other hand. Some rocks, like limestone, are quite easily soluble by water that penetrates into the earth, while others, like clay rocks, are either insoluble, or so little open to solution that they may, for all practical purposes, be classed as insoluble. Others still, perhaps neither soft nor soluble, are, nevertheless, easily worn away because some or all of their minerals are readily altered and disintegrated, causing the rock to crumble. Such a change is often called rock decay, and the use of the word is warranted because much of the change is due to oxidation as in other forms of decay. Even the hardest rocks are sometimes subject to rapid decay because of the unstable condition of one or more of their constituent minerals on exposure to the air or to percolating water. Lavas furnish illustration of this, for the minerals that separate out from the molten rock in its cooling are not always compounds that can retain stability in the air.

Usually the degree of resistance that rocks present to denudation is due to a combination of two or more of the conditions mentioned in the preceding paragraph. A rock that easily disintegrates is called soft, though these terms are not used to signify actual hardness or softness. It is better to use the term *weak* or *non-resistant* for those rocks that are easily worn away and *resistant* for those that withstand the attacks of denudation. Granite, quartzite, and gneiss are resistant rocks; limestones, clays, sands, and many lavas are weak rocks. Since there are those differences in resistance of rocks, as the surface of the lands is worn away, it is worn at variable rates, according to the nature of the surface rock. Therefore many of the details of topographic forms are the result of the condition of the underlying rock.

Besides composition there are other factors of importance in guiding the rate of removal of rocks by denudation. Some rocks, for example, are porous, while others are quite dense, and therefore the rate at which water can enter the rock and help in its disintegration varies. Many rocks are crossed by natural breaks, called *joint planes*, into which water freely enters, and sometimes these joint planes are very numerous and close set, aiding greatly in opening the rocks to the attacks of the agents of disintegration. The laminæ of such metamorphic rocks as schist and the layers of the sedimentary strata are also aids to percolating water, often furnishing paths of entrance into the rocks. There is much difference in the effect of this influence according to the attitude of the layers.

When deposited in the sea or lake or river, sedimentary strata are commonly laid down in horizontal or nearly horizontal position;

but when uplifted above the sea, especially in mountains, these layers are often tilted out of the horizontal, and even into vertical position, forming *folds*. When rock layers are broken and then uplifted on one side of the break, there is said to be a *fault*. When folded rocks are truncated by erosion and horizontal beds are afterward laid upon the eroded edges of the inclined layers, the feature produced is spoken of as an *unconformity* (Fig. 24).

Since rocks in different attitudes, or with different degrees of porosity, or with different development of joint planes are subject to the attacks of denudation at different rates, these are also important factors in determining details in land form. Denudation works selectively, removing most rapidly those rocks which present the weakest resistance, whether as a result of mineral composition, or structural weakness, or attitude, or a combination of two or more of these.

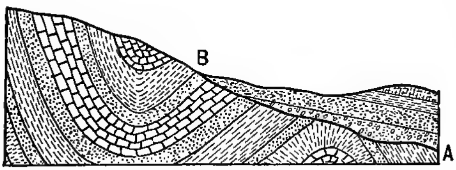


FIG. 24. — An unconformity along the line *AB*.

Mantle Rock or Regolith. — While in mountains, and in other places of steep slope, the rocks of the earth's crust outcrop, elsewhere the rocks are commonly mantled by a layer of unconsolidated rock fragments of varying thickness for which the names *mantle rock* and *regolith* have been proposed. Over much of the land surface this mantle of rock débris has been derived directly from the decay and disintegration of the rock on which it rests; but over large areas it has been transported by wind, streams, glaciers, or other means from a place of origin to its present place of rest. This layer of rock waste, mantling a large part of the land surface, may be but a few inches thick, or it may be scores or even hundreds of feet thick. It is of vast importance in physical geography, for it acts as a blanket protecting the underlying rock from rapid disintegration; it furnishes sediment to streams; and it is in its upper portion that most of the vegetation of the land grows.

The upper portion of the regolith, in which the vegetation grows, is called the *soil*, a loose mixture of rock fragments prevailingly of small size, ordinarily somewhat porous, and with a greater or less admixture of plant fragments. In some swampy places the soil is mainly of organic origin, but such soil is of a different origin from that which is now being considered. There is much difference in the texture of the soil, which varies from compact clay to sand and gravel; in porosity, which ranges from almost impervious clay to loose sand and gravel; in colour, which may be black, brown, red, or yellow; in thickness, which may vary from an inch to three or four feet; and in mineral and chemical composition. According to these variations the adaptability of the soil to cultivation varies greatly. Some soils are very fertile and the seat of thriving agricultural industries, while others are thin or sterile and quite unsuited to agriculture.

The soil grades downward into the *subsoil*, which closely resembles and is of the same origin as the soil; but it lies below the zone of plant growth, and contains little or no admixture of organic matter. The subsoil, in turn, grades into the underlying rock from which it is derived, where the mantle rock has been formed by disintegration of the bed-rock; or, if transported, the subsoil rests directly upon the rock upon which it was deposited. Everywhere beneath the mantle of soil lie the rocks of the earth's crust, in some places sedimentary, in others igneous, or metamorphic.

Geological Ages

For convenience of reference geologists have divided the strata of the earth's crust into groups, systems, series, and stages, corresponding to eras, periods, epochs, and ages of geological time. This is done chiefly upon the basis of the fossils contained in some rocks, especially those of sedimentary origin. As is shown in the table below, there was a time when there were no animals living upon the earth which were higher in development than the fishes. Accordingly if strata contain remains of birds, it is clear that these are not of such ancient date. Careful studies of all sorts of animals and plants of the past, as preserved in the rocks, make it possible for the paleontologist to determine the relative ages of the rocks with considerable precision, although no attempt is made to show how long ago, in years, the strata were formed. The relative ages of igneous and metamorphic rocks are made out from the structural relationships, the unconformities, etc. Indeed it is possible for students of stratigraphic geology to determine not only the nature of ancient life, but in some cases, from a study of the rocks themselves, to describe the conditions under which this life existed on land and sea, and even the climate of past geological ages. Such a description of ancient conditions on the earth's surface is called *paleogeography*. The presence of walrus bones in the sands of New Jersey, the existence of the musk ox as a fossil in Arkansas, and of the reindeer in southern New England, tell a definite story of colder climate in these parts of the United States not very long ago. Similarly, the fossil plants found near Toronto suggest a milder climate than the present. The growth of vegetation which was subsequently consolidated into coal in Antarctica and Greenland, the precipitation of gypsum and salt in Kansas, the formation of ancient glacial deposits in South Africa, of extremely old delta accumulations in the Appalachians, and of sandstone of eolian origin in Australia, all furnish facts for deciphering the paleogeography of one or another of the remote geological periods.

The use of such a standard geological column as is given on page 32, in which the oldest eras and periods are printed at the bottom, is a matter of international agreement.

GEOLOGICAL COLUMN

Era	Period		Condition of Life
CENOZOIC TIME (Age of Mammals)	*Quaternary, or Pleistocene*		Man assumes importance, particularly in latter part of the Quaternary which is known as the Recent Period. Glacial Period in first half.
	Pliocene	*Tertiary*	Mammals develop in remarkable variety, and to great size, while reptiles diminish.
	Miocene		
	Oligocene		
	Eocene		
MESOZOIC TIME (Age of Reptiles)	*Cretaceous*		Birds begin to be important; reptiles continue; and higher mammals appear; land plants and insects of high type.
	Jurassic		Reptiles and amphibia predominate.
	Triassic		Amphibia and reptiles develop remarkably; low forms of mammals appear.
PALEOZOIC TIME (Age of Invertebrates)	*Permian Carboniferous*		Land plants assume great importance.
	Devonian		Fishes are abundant. They began in the Silurian and continue, though with many changes, to the present time.
	Silurian Ordovician		Invertebrates prevail. They continue abundant to the present time, but are of different kinds.
	Cambrian		No forms higher than invertebrates.
PRE-CAMBRIAN TIME (Few fossils known)	*Algonkian Archean*		Mostly metamorphic rocks; perhaps, in part, original crust of earth.

Some geologists and geographers would change this column in minor details. In France and England, for example, the Paleozoic and Mesozoic are still sometimes called "Primary" and "Secondary," but Ordovician is not separated from the Silurian, while "Liassic" may be introduced after Triassic; in England, Devonian may be called "Old Red Sandstone"; in Germany, Permian may be called "Dyas," and Quaternary may be divided into "Diluvium" and "Alluvium"; in the United States there are proposals to divide the Carboniferous into "Mississippian" and "Pennsylvanian"; not to separate Permian from Carboniferous; to separate the "Comanchean" from the Cretaceous; to divide the Tertiary merely into Eocene and Neocene; and to divide Quaternary into " Pleistocene " and " Recent." Various substitutes have been suggested for Pre-Cambrian, including " Azoic " and " Proterozoic," but Pre-Cambrian is most commonly used.

Maps and Map Projection

The ideal way to represent the features of the earth's surface is by a model or relief map. The globe is a small model of the earth and photographs of the models or relief maps of the continents are shown in Figs. 380, 381, 382, 383, and 385. Flat maps, however, are necessary for use in books; but these, though convenient, have disadvantages, especially in the difficulty of representing the third dimension, — height or depth. When we come to represent a globular area, like the earth, upon a flat map, there are great difficulties to overcome, and the whole earth has to be shown in two halves or *hemispheres* (Figs. 18 and 277). As we cannot flatten out the curved surface it is, even then, necessary to represent it as if projected upon a flat surface, and there are several such plans, or *projections*, the details of which may be found in a text-book of mathematical geography.

One scheme is to project the parallels and meridians, and the features of the earth, upon a piece of paper, rolled up like a cylinder. The unrolled map has the meridians all parallel instead of converging, and the parallels all of the same length. This is *Mercator's projection* (Fig. 321). The distances east and west are all distorted, except on the equator, and are too great near the poles, as is seen by comparing the width of Greenland on Fig. 321 and on a globe (Fig. 18). *Orthographic*, *Stereographic*, *Globular* or *Equidistant*, *Homolographic*, and many other projections vary with the assumed position and distance of the observer when projecting the lines, and result in less distortion than in Mercator's projection. This is seen by comparing Greenland in Fig. 486 (Homolographic projection) with the same area in Fig. 321 (Mercator's projection). There are several *Conical Projections*, which suppose the area of the map to be projected upon a cone or a series of cones, similar to the cylinder of Mercator's projection. These result in far less distortion (see Greenland in Fig. 172, on a conical projection). The projection most commonly used for small areas is the *polyconic*.

Scale. — It is also necessary to use a scale of reduction in representing areas upon a map, an inch upon the map equalling so many miles or so many feet in the area mapped. These scales are sometimes represented on maps by a printed statement, as *one inch equals one mile*, and also by a *graphic* scale of miles, as on Figs. 42 and 52, where there is a line at the bottom, divided into miles and parts of miles, for measuring distances upon the map. Sometimes the scale is also represented by a fraction or a ratio, as in the fractional scale $\frac{1}{63360}$ or 1 : 63,360, meaning that one inch on the map is equal to 63,360 inches in nature. This and its multiples are much used in

Great Britain. As 63,360 inches (12 times 5280) make a mile, the scale of this map is exactly one inch to one mile. The scale 1 : 62,500 (Fig. 115) is close to that of 1 inch to 1 mile, and this and directly related scales are commonly used in United States. The departure from the 1 : 63,360 scale is based upon convenience in relation to the decimal system; for 1 : 62,500 is related in a simple way to the scales of 1 : 125,000 and 1 : 250,000 and 1 : 1,000,000. In France, Germany, and other parts of Europe the decimal scale of 1 : 100,000 is very common on government maps.

There is usually no scale of miles on a map of Mercator's projection because of the distortion. Scales vary according to the degree of

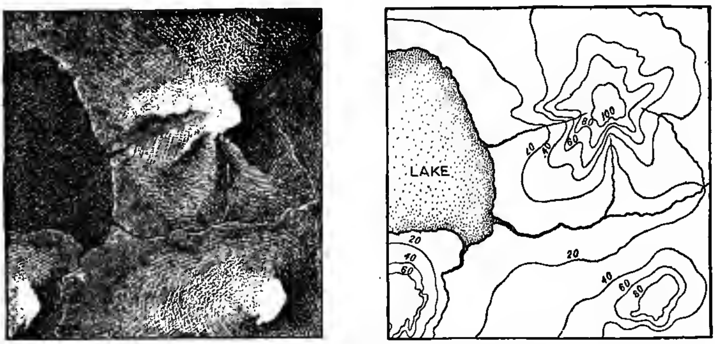


Fig. 25. — A shaded map on the left, showing hills, valleys, and a lake. On the right is a contour map of the same area with a contour interval of 20 feet.

detail to be represented on the map, and the use to which it is to be put.

Relief. — Heights and depths may, of course, be represented upon the map by figures, but it is also desirable to show the actual shapes of the land forms upon the surface of the earth. This may be accomplished in several different ways. On the model it is, of course, done by actually carving a minute representation of the real thing, with some scale of reduction (see the Rocky Mountains, for example, on the photograph of the model of North America, in Fig. 382). On a flat map this is impossible except by photography, and a variation of the same method is a system of shading the northwest or some one side of all elevations, giving an effect similar to what one would see if the area were seen in daylight, with one side of each hill and valley illuminated by the sun (Fig. 25).

Contours. — Another method is to draw lines through all points equally high above sea level. These lines are called *contours*, and they represent the edges of parallel planes, such as sea level, and the successive levels to which the slopes would be submerged if the land sank 20 feet, 40 feet, 100 feet, etc. The vertical distance between these lines is called *contour interval.* Contours are closely spaced on steep slopes and are far apart on gentle slopes. They bend up-stream in valleys and down hill on ridges. Figures 25, 314, 315, and 318 are contour maps.

The space between contours may be shaded, as in Fig. 391, where the deeper and deeper tints show deeper and deeper water. The height of the land may be shown in a similar way (Fig. 332).

Hachures. — Another plan of showing relief is to omit the contour lines, but to draw short lines down the slopes, as in Fig. 26. These short lines are called *hachures*, and hachure maps (as Fig. 306) give a vivid idea of the way a region looks, for the little lines are short and close together on steep slopes, long and far apart on gentle slopes, and

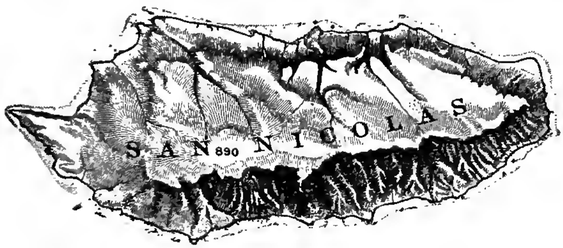


FIG. 26. — A hachure map. (U. S. Coast and Geodetic Survey.)

are omitted on flats. They are commonly used on United States Coast and Geodetic Survey maps, for example, because they give the mariner a general idea of the appearance of the country near the coast. Hachures do not give as specific information as contours, by which one can tell exact heights throughout the area of the map, and the latter are generally used on United States Geological Survey maps, as well as in many other countries.

REFERENCES TO LITERATURE

Simon Newcomb. Elements of Astronomy, New York, 1900.
C. A. Young. Manual of Astronomy, Boston, 1902.
David Todd. New Astronomy, New York, 1897.
F. R. Moulton. Introduction to Astronomy, New York, 1906.
A. Geikie. Text-book of Geology, 4th edition, 2 vols., New York, 1903.
J. D. Dana. Manual of Geology, 4th edition, New York, 1895.
Joseph Le Conte. Elements of Geology, New York, 1877; 5th edition, edited by H. L. Fairchild, New York, 1903.
T. C. Chamberlin and R. D. Salisbury. Geology, 3 vols., New York, 1905.
W. B. Scott. Introduction to Geology, 2d edition, New York, 1907.
W. H. Hobbs. Earth Features and their Meaning, New York, 1912.
A. W. Grabau. Principles of Stratigraphy, New York, 1913.
F. W. Clarke. The Data of Geochemistry, Bulletin 330, U. S. Geological Survey, 1908; 2d edition, *ibid.*, Bulletin 491, 1911.

Mineral Resources of the United States. An annual publication of the United States Geological Survey.
E. S. Dana. Minerals and How to Study Them, New York, 1895.
L. F. Pirsson. Rocks and Rock Minerals, New York, 1908.
J. F. Kemp. Handbook of Rocks, New York, 1896, 1900.
B. Willis, R. D. Salisbury, and Others. Outlines of Geologic History, Chicago, 1910.
B. Willis. Index to the Stratigraphy of North America, Prof. Paper 71, U. S. Geological Survey, 1912.
C. Schuchert. Paleogeography of North America, Bulletin Geological Society of America, Vol. 20, 1910, pp. 427–606.
W. E. Johnson. Mathematical Geography, New York, 1907.
S. Günther. Handbuch der Mathematischen Geographie, Stuttgart, 1890.
Henry Gannett. Manual of Topographic Methods, Monograph 22, U. S. Geological Survey, 1893; *ibid.*, Bulletin 307, 1906.
E. A. Reeves. Maps and Map Making, London, 1910.

CHAPTER II

WEATHERING AND ROCK DISINTEGRATION

Instances of Disintegration

Freshly quarried rock seems hard and indestructible; but so too does a piece of steel from a blast furnace. Yet it is a well-known fact that the latter, on exposure to the air and dampness, rusts, decays, and slowly crumbles. So, too, do rocks, though the time required for their disintegration may be longer. The process might escape the casual observation in the brief period of a human lifetime, but it becomes very noticeable when its effects are magnified by the passage of time. For example, headstones placed in cemeteries a century or two ago have often so crumbled that the inscriptions upon them are now quite obliterated. In old buildings the effects of disintegration of the building stone are often very noticeable. For instance, the stone in Westminster Abbey in London, put in place in the thirteenth century, has during the seven centuries of exposure to the atmosphere so crumbled that even the most casual observer must be struck by the change; and the gargoyles and other ornamental parts have so crumbled that many of them now are mere shapeless masses of stone. Evidence that the same changes are in process in the rocks of the earth's crust is clear and complete.

As stated in the last section, the rate of rock disintegration varies with the nature of the rock. That in Westminster Abbey is a loose, porous, weak rock which crumbles readily; but even the most resistant of rocks are subject to the same changes, though at slower rates. There is a variation in rate also according to the nature of the exposure and to the climate. The latter point is illustrated by the case of the Obelisk in Central Park in New York City. After remaining unchanged for many centuries in the desert climate of Egypt, this obelisk was brought to the damp, frosty climate of New York, and almost at once it began to crumble, and at such an alarming rate that it became necessary to protect it by a coating of glaze. In Brazil the decomposition of the rock goes to a depth of 100 to 300 feet.

Agents of Weathering

Relation to the Atmosphere. — Such rock decay, or disintegration, is often called *weathering*, for the chief agents by which the decay is brought about are, directly or indirectly, related to the atmosphere, and to weather conditions. It is, however, a complex process, in which the weather is only one of the elements, and from that standpoint the term may be somewhat misleading.

The Three Chief Agencies. — There are three primary agents involved in weathering: (1) water, (2) atmospheric gases, (3) organisms. Independently or in coöperation these work toward the one result of rock disintegration; and each of the agents operates both by mechanical and by chemical processes. Coöperating with weathering in making it more effective are gravity and the agents of erosion, by means of which the disintegrated rock fragments are more or less completely removed from the rock from which they are derived. Where this removal is incomplete, the rock fragments remain as mantle rock, thus serving as a partial protection to the bed rock against some of the agencies of weathering.

The Work of Water

Although the process of weathering is the combined result of the action of several agents, the nature of this process will be more easily understood, if the agents be studied one by one, and their action considered, for the time being, as if weathering were the sole process at work.

Chemical Work of Water. — Among the agents, that of water is surely by far the most important. Moisture in the air together with the atmospheric gases are potent causes for chemical change, but this action is mainly confined to the very surface of the exposed rocks. Percolating water, on the other hand, enters into the interior of rocks and, accordingly, greatly extends the process of weathering. The rate of weathering is, therefore, greatly influenced by the porosity of the rocks. Some rocks are quite impervious to water, but the great majority are sufficiently porous for the fairly easy entrance of percolating water. Some, indeed, are so porous that the rain-water quickly soaks into them, as in sand beds. In the Bermuda Islands, where, although in a rainy climate, no fresh water is to be found, the supply of drinking water must be obtained from rain-water stored in cisterns.

Rock porosity is dependent primarily upon the fact that the minerals or grains of which the rock is composed are not thoroughly bound together. There are minute pores or cracks around the grains or minerals, through which the water finds more or less ready passage according to the size of the cavities. The minerals themselves are often traversed by minute cracks, such as open cleavage planes, along which water can penetrate, thus finding admission into the very heart of the minerals. Furthermore there are larger cracks, such as joint planes, along which still greater volumes of water find entrance into the earth.

If the percolating water were pure, the chemical change or solution resulting from its entrance into the rocks would not be great; but no percolating water is pure, for in its passage through the air it carries with it atmospheric gases, notably oxygen and carbon dioxide, and in its passage through the soil it is also armed with organic acids. Thus charged, water becomes a potent agent of solution of some minerals and of decay of others. Dissolving one kind of mineral in a rock, even to ever so slight an amount, and only around its boundaries, helps to reduce the cohesion of the mineral grains, and thus induces crumbling. In some rocks the soluble minerals are present in such amounts as to make this cause for rock disintegration of much importance.

Minerals that are not directly soluble are often open to change in chemical composition in the presence of water. The nature of this change is not unlike that to which iron is subject. A nail, for example, exposed to damp air, first becomes dull, then rusty, and ultimately is reduced to a powder of iron rust. In this case water and oxygen from the air have formed a chemical compound with the metallic iron, changing the form, the chemical composition, the hardness, and even increasing the weight of the original iron. This change is oxidation and hydration, and the resulting iron rust is the hydrated oxide of iron, consisting of iron, oxygen, and water, chemically combined. Similar changes occur in some of the rock-forming minerals. There are, for example, certain minerals containing iron; and oxygen and water acting upon these produce an iron rust of the same kind as that resulting from the rusting of a nail. The red and yellow colours so common in rocks and soils are stains due to the rusting or decay of iron minerals.

Other minerals, such as feldspar, so hard that they cannot be scratched with the knife, and so clear and transparent as to be glassy, slowly suffer chemical change in the presence of water, oxygen, carbon dioxide, or other substances, so that they finally lose their glassy appearance, are no longer hard, and are transformed to a white powder which crumbles between the fingers. As in case of solution, so here, the change is most readily carried on along the crevices through which water percolates. Thus it happens that the minerals of rocks, when studied under the microscope, are often found to be decayed around the boundaries, or along the cleavage planes, while elsewhere they are fresh and unweathered. By the crumbling of some of the mineral grains in a rock it is so weakened that disintegration naturally results. Furthermore some of the decayed mineral may be actually removed from the rock by the percolating water, for among the products of these chemical changes there are often produced compounds which are easily soluble, although the original mineral was insoluble.

The rate at which the chemical work of water proceeds, naturally varies greatly according to conditions, such as the amount of rainfall, the composition of the rock, the porosity of the rock, the exposure of the rock, the chemical composition of the water, and the temperature. Speaking generally, this form of rock disintegration is most rapid and most effective in warm, humid climates, where there is an abundance of water, there is much decaying vegetation to supply carbon dioxide and organic acids, and the temperature of the percolating water is high. It thus happens that in such regions the mantle rock is often very thick, and the bed rock is decayed to a great depth, even scores of feet below the surface. It should be noted, however, that one reason for this thick blanket of disintegrated rock in tropical regions is the protection that vegetation gives the unconsolidated mantle rock against such agents of erosion as the winds and running water. The chemical work of water in rock disintegration is least effective in arid climates, where there is little moisture, and in frigid zones, where the soil is frozen so that percolating water is unable to enter.

FIG. 27. — Percolating water that has frozen after seeping out of the rock along joint planes. Within the rock it is a mechanical agent of weathering.

Mechanical Work of Water. — The freezing of water is a potent agent of rock disintegration, for when ice is formed in rock crevices and cavities (Fig. 27) it exerts such a strong pressure against the cavity walls that the rock may be broken. As the water changes to ice, it expands and must, therefore, have more room, which, if in a closed or nearly closed cavity, it can obtain only by enlarging the cavity. It is for this reason that bottles of water burst when exposed to freezing; and even bombshells and cannon have been broken by the powerful force of expanding water during freezing. At a temperature of 30° F. a pressure of about 138 tons to the square foot is exerted by the ice forming in a closed cavity.

To this enormous force rocks near the surface of the earth in regions of frost are frequently subjected. The water in the microscopic crevices, as well as that in the larger cracks and openings, must, on freezing, find space for increase in volume. Where the cavities are open, the full force of the expansion will not be exerted; but even here some force is applied against the cavity walls, the amount depending upon the difficulty with which the ice is forced out of the cavity. As a result of the freezing of water in the rock cavities, disintegration is caused, both by the breaking off of minute bits, and by the disruption of large masses. With alternate thawing and freezing, such as accompanies the succession of warm days and cold nights, the frost work is repeated again and again during a single season. This cause for rock disintegration is, of course, confined to the colder regions of the earth, and it naturally assumes greatest importance in the polar regions and in high mountains (Fig. 30). In such places, in summer, there is frequent alternation of temperature from above to below the freezing point, and there is abundance of moisture. There, frost action is the principal agent of weathering. By it, the exposed bed rock is so disrupted, that its surface is covered with a layer of loose, angular, frost-riven blocks. For example, on certain low, flat-topped hills in Spitzbergen one may walk for a mile or more over a field of angular rocks with no bed rock and no soil to be seen, while on the steeper slopes the large angular fragments may often be seen and heard to break away from the bed rock under the influence of the frost action, and to fall to the cliff base. This powerful quarrying work of frost is similarly potent among lofty mountains where there are extensive fields of frost-riven rock fragments (Fig. 30) on the more gentle slopes, and accumulations of them at the cliff base. Frost action is one of the most important and most rapidly acting causes for the lowering of lofty mountain peaks and ridges.

Frost action is an effective agent of weathering in cool temperate regions, though its effects are far less noticeable than in higher latitudes and altitudes. The breaking away of rock fragments from cliffs, and the disruption of exposed rock occur here as in colder climates; and the effect of frost upon the soil is often very noticeable. As thawing and freezing occur, the ice that forms in the porous soil, seeking relief on expansion by rising toward the surface, pushes before it soil particles, stones, and even boulders; and at the same time, the freezing of water in the soil particles themselves helps to break them up and make the soil finer in grain. Frost work, is, therefore, an effective agent in rock disintegration and in soil formation; but its activity is limited to a much narrower zone than that of percolating water, for it is essentially confined to that surface film of soil or rock in which there can be frequent alternation of temperature above and below the freezing point. Therefore frost work is most effective in those places where the slope is sufficiently great for the frost-riven blocks to freely fall away when disrupted; while on lesser slopes its effectiveness diminishes as the mantle of weathered rock accumulates.

Atmospheric Work

The air is an agent of erosion, a subject treated in a later section. It is also effective in rock disintegration, acting in this respect both directly and indirectly through its influence upon temperature. Like water, it works both chemically and mechanically.

Chemical Work of the Air. — In a dry state the air has little power for chemical change in rocks, but with its vapour content, the gases, notably oxygen and carbon dioxide, become important agents of rock change. The processes which result from the action of water vapour, oxygen, and carbon dioxide in the air are essentially of the same kind as those of percolating water, already discussed — namely, solution, oxidation, hydration, and other changes in the chemical composition of the rock-forming minerals. But this action is confined practically to the very surface, although, as we have seen, the extension of weathering into the rock beneath the surface is greatly aided by the oxygen and carbon dioxide supplied to the percolating water, which itself is supplied to the atmosphere as vapour condensed to rain. Thus indirectly the atmosphere is a very important aid to rock disintegration by means of chemical change.

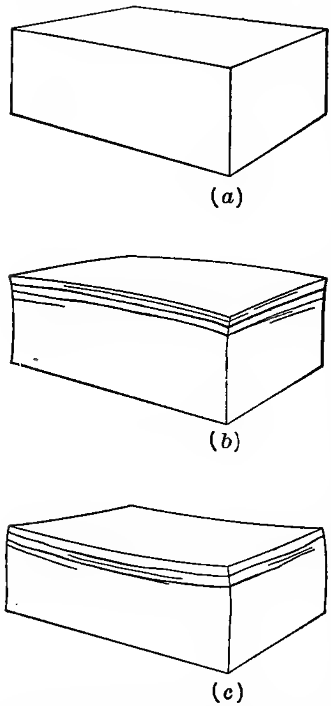


FIG. 28.—Van Hise's diagram to show the effect of heating the surface of a rock: conditions (*a*) at uniform temperature, (*b*) with expansion of the surface when heated, (*c*) with contraction of the same surface when cooled.

In its direct influence upon the chemical changes in rocks, the air is of least importance in arid and desert lands where the water vapour content is least; and it is most effective in humid regions. The chemical work of the air is increased by the addition of certain foreign substances. For instance, in large cities, the abundance of carbon dioxide, coal gases, and other impurities increases the activity of the air in this respect. The presence of salt in the air, brought to the lands by the east winds, produces a noticeable effect at Gloucester, Mass., where, after a few years' exposure, chimneys lean to the east because of the action of the damp salt air in removing the cement between the bricks.

Mechanical Work of the Air.—Directly the atmosphere is of little importance as an agent of weathering by mechanical means, but indirectly, through its influence upon temperature, it is an effective agent. In parts of the earth, notably in dry climates, there are great ranges in temperature during the day, sometimes as much as 70° or 80°, and even more. The rocks become even warmer than the air, due to absorption of heat, and their temperature in the full sunlight may rise to as much as 120° or 130°, while at night, by radiation, there is a rapid fall to 60° or less.

Warming causes expansion, and cooling contraction, so that there is a constant straining of the minerals, analogous in a lesser degree to that caused in a piece of glass when it is rapidly heated over a flame, when, as is well known, it will snap into pieces. This straining is differential, for some minerals expand and contract at one rate, some at another; and some minerals, such as those that are black in colour, reach a higher temperature than others, such as the white and transparent minerals. Consequently, as rock is warmed there is, in the first place, an expansion of the entire mass whose temperature is raised, and there is also set up within the warmed area a series of strains of complex nature by which the minerals tend to pull apart along their boundaries.

Exfoliation. — As a result of these changes, through alternate expansion and contraction, the outer layers of rocks are weathered and made to crumble. Not only are small grains loosened, but layers are cracked off and peeled away, giving rise to the phenomenon called *exfoliation.* Some varieties of rock exposed to this phase of weathering present a layered outer structure resembling that of an onion, from which it is possible to pry off one or more layers, already loosened, but not yet quite ready to fall away naturally (Fig. 28).

Exfoliation is a phenomenon especially common in arid climates where the daily changes of temperature are especially rapid; but it is also noticeably present on high mountains, and is not absent in humid regions. Although capable of production by temperature change alone, exfoliation is often the result of a coöperation of causes in which are included change of temperature, chemical change, and frost action.

The Work of Organisms

Many forms of life, both animal and plant, are contributing toward the disintegration of rocks, either directly or indirectly, and both by chemical and mechanical means.

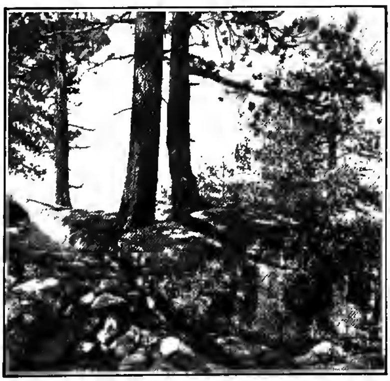


Fig. 29. — The work of tree roots in weathering. (Gilbert, U. S. Geol. Survey.)

Work of Plants. — Lichens, clinging to rock surfaces, loosen and pry off particles by mechanical means as they grow, and they aid in chemical changes, both directly by abstracting mineral substances, and indirectly by conserving moisture on the rock surface and supplying organic acids to it. Higher plants operate in the same directions both upon the bed rock and upon the soil. As the plant roots grow, they often exert a powerful force, sufficient to wedge off both small and large rock fragments (Fig. 29), and to break up the soil particles; and by the decay of the plant fragments on and in the soil, organic acids are produced which add to the efficiency of percolating water as an agent of chemical change.

In the production and comminution of soil there is a process of high importance, the exact operation of which is at present only partly understood. This is the abstraction of mineral matter from the soil, by which a portion of the disintegrated rock is taken into the plant in solution, and, on the death of the plant, left on the surface in a finely-textured state. In this way, by the action of multitudes of plants, there is a slow reduction and wastage of the soil. At least a part of this process is performed by bacteria, but an efficient aid in it is the hairlike roots of the plant.

Work of Animals. — Animals aid in rock disintegration mainly by work upon the already partly disintegrated rock of the soil. Among those animals which are efficient aids to weathering are the burrowing animals, such as the ground squirrel, the prairie dog, the woodchuck, the earthworm, and the ant. All of these aid to some extent by furnishing chemical substances to percolating water; by bringing soil particles to the surface and hence to a zone of greater exposure; and by rendering the soil more porous and, hence, more open to percolating water. Some of them, like the earthworm, also aid in the comminution of the soil by passing it through their intestinal tract. Among the burrowing animals the earthworm in temperate climates and the ant in the warmer regions are by far the most important, and are to be reckoned as among the significant agencies in the production and comminution of soil, one of the final stages in rock disintegration.

Man, in his civilized state, has come to be one of the most effective organic agents in weathering. By tunnelling into the earth, by quarrying, by excavating, by ploughing, and by removal of natural vegetation, he is aiding in the processes of weathering in most important ways; but this work is only recent and, from the standpoint of the development of land forms, the influence of man as an agent of weathering may be ignored.

Variations in Rate of Weathering

While each of the agents mentioned above, acting in each of the ways described, is by itself a factor in weathering, the process of rock disintegration, viewed broadly, is the result of a complex interaction of all these agents, one dominating here, another there. The general result is to cause a slow wasting of the surface, the production of a layer of disintegrated rock of variable thickness, and the reduction of solid rock to sufficient degree of softness or comminution to permit of ready transportation by the agents of erosion.

Influence of the Rock. — The rate at which weathering succeeds in this result depends upon a variety of conditions, some inherent in the rock, others dependent upon the nature and intensity of the effective agents in a given locality. The rocks themselves vary (*a*) in porosity, (*b*) in the solubility of the component minerals, (*c*) in the stability of the minerals, that is, in the ease with which they undergo chemical change in the presence of water and atmospheric gases. Rocks composed of relatively insoluble and stable minerals, so closely set as to reduce porosity to a minimum, are disintegrated very slowly, while porous, soluble rocks, or rocks with unstable minerals, weather rapidly.

Influence of Climate. — Both the rate and the nature of the weathering processes vary with the climate, one form, like frost, dominating in cold climates; another, like solution and chemical change, in warm, humid climates; and a third, like the effect of temperature change, in arid climates. Speaking generally, weathering is least rapid in arid climates, for there the work of water and of life is reduced to a minimum; but whether the rapid disintegration by frost action in cold climates is a more effective agent of weathering than the solution and chemical change of warm, humid regions, we are not in a position to state.

Influence of Structure. — In certain exposures rock weathers far more rapidly than in others. If, for example, there is a plane of more easy percolation in a rock, it is important whether that plane lies horizontally or vertically, for, if the latter, it offers a freer passage of water into the rock. Again, it is a matter of much importance, whether the rock is crossed by many (Fig. 27) or by few joint planes, for, if the former, the extent of the rock surface exposed to the air and to the effects of freely moving water is greatly increased. Even more important than either of those is the question whether the rock is exposed to the air or is protected by mantle rock.

Influence of Slope. — The most widespread and efficient cause for the exposure of rock to the air, in spite of the constant disintegration to which it is subjected, is steepness of slope, as a result of which fragments fall away under the pull of gravity as fast as they are dislodged. On such slopes weathering may maintain its activity, and rock disintegration proceeds at a rapid rate. It is partly because of the abundance of such slopes among lofty mountains that the rate of weathering there is rapid. Other causes for the maintenance of bare rock surfaces are the action of the wind and running water, which strip away the rock fragments as fast as weathering dislodges them.

Influence of Vegetation Cover. — A final important influence in rate of weathering is the extent of the vegetation cover. While plants are aids to weathering in significant respects, as outlined above, they exert, on the other hand, an important conserving effect, protecting both soil and rock from some of the agents of weathering, and, by their protective influence, and by the tangle of roots which they send into the soil, tending to hold the mantle rock in its place, and thus keep the bed rock protected by the blanket of products of disintegration which the agents of erosion tend to remove. It is probable that the general protective effect of vegetation is far more important than its destructive effect in directly and indirectly assisting in the processes of weathering. Where a land surface bears but little vegetation, as in arid lands, erosion by wind and running water has a much greater tendency to remove the soil cover than in humid forested areas. The stripping off of vegetation in a humid climate has the same tendency of permitting the mantle of disintegrated rock to be removed, and the bare rock to be exposed, instances of which abound in regions where man has carelessly interfered in nature's balance. In this respect, as in others, man is to be reckoned as one of the animals contributing toward rock disintegration.

Results of Weathering

The prime result of weathering is the transformation of resistant rock to a fragmental condition, in which its removal becomes an easier task for the agents of erosion. It is, therefore, a coöperative process in the denudation of the land, preparing the rock for removal. Incidental to this are a series of phenomena, dependent upon the rate of preparation, the rate of removal, and the nature of the process of removal.

Influence upon Topography. — Since the rate of disintegration varies, according to the climate, the slope, and the nature of the rock, the influence of weathering varies from place to place. In cold climates gentle slopes are covered with a field of angular blocks of frost-riven rock; in warm climates similar slopes are clothed in a mantle of soil; on steep slopes, rugged rock cliffs appear, while gentle slopes are smoothed with a blanket of disintegrated rock.

Even more noticeable than this, however, is the influence exerted by weathering upon rocks of different degrees of resistance. Weathering is a delicate tool of rock sculpture, detecting even minute differences in rock texture and composition, and etching them out into relief. A fossil, embedded in a rock, will be etched into relief if more resistant than the enclosing matrix, and even its delicate markings will be brought out clearly; or, if less resistant, its site will be transformed to a cavity by the work of weathering. Minerals that are more resistant than their neighbours will be etched into relief, and cavities will be worked into the surface on the sites of the weaker minerals.

Still larger differences in rock resistance are discovered by weathering, and the topography influenced thereby. In sedimentary strata, for example, the weaker beds are eaten away and the resistant beds left in greater relief. Here weathering is only the agent of disintegration, but coöperating with it are agents of removal by which the effects of disintegration are continued and made more manifest. By the combined action of disintegration and removal of the products of disintegration by gravity, wind, or water, resistant beds are brought into prominence, on a small or large scale according to the degree of difference in resistance of the associated strata.

The resulting topographic form naturally varies, not only according to the nature of the rock, but its attitude. Thus horizontal strata are etched along the horizontal outcrop, giving rise to alternate linear cliffs of resistant rock and less steeply inclined intermediate slopes of weaker rock (Fig. 67). Inclined strata give rise to ridges where the resistant rock outcrops, and to intermediate valleys where the rocks are weaker. Massive rocks weather into forms quite different from those of bedded rocks in which there are alternations in degree of resistance from layer to layer; and minutely jointed rocks weather both at a different rate, and into different forms from those that are not greatly jointed.

There is, therefore, a vast difference in the rate of weathering, according to structure, texture, and attitude of rocks, and these differences are of fundamental importance in the determination of topographic form. It must be clearly understood, however, that the result is not the sole product of weathering, but of coöperation between weathering and erosion. It is a part of the lowering of the surface in which some portions go faster than others. This process may be stated as a law as follows: that *in the general reduction of the surface of the lands those rocks which are resistant to weathering tend to lag behind those which are less resistant, and, therefore, to give rise to prominences.* It is to the operation of this law that we owe most mountain peaks, most plateau escarpments, and other topographic forms, the nature of which will serve as topics for later discussion. A large part of the topographic detail of the lands is dependent in a basal way upon the discovery by weathering of differences in rock structure, texture, and attitude.

The Aid of Weathering to Agents of Erosion. — As rock disintegrates, the products of disintegration are subject also to removal by gravity, wind, and water, and, in the course of their removal, these products are used by the agents of erosion as tools in their work of erosion. Thus weathering is an aid to erosion, not merely in disintegrating the resistant rocks so that they can be more easily worn away, but also in giving to the agents of erosion rock fragments with which they can scour and grind away the resistant unweathered rocks. Were it not for this aid of weathering, the rate of erosion by wind, waves, and rivers would be far less rapid.

The weathered particles are transported by the agents of erosion to a place of rest, there accumulating in strata of sedimentary rock. Traced back to their ultimate source, most of the materials in the sedimentary strata have been derived from some previous state of consolidated rock, and the first step in the process of their removal to a place of deposit has been the disintegration of the solid rock by the agents of weathering. It is, therefore, proper to consider weathering as fundamentally important in the derivation of the vast series of sedimentary strata which have accumulated in the upper layers of the crust of the earth during the long ages of past denudation.

Deposits of Weathered Rock Fragments. — While some of the products of rock disintegration are moved by the agents of erosion far away from their source of origin, other portions come to rest close by their source. Among these are deposits in whose movement gravity has been the prime agent of transportation.

Talus. — This finds typical illustration in those deposits called *talus*, which accumulate at the base of cliffs by the frequent fall of rock fragments loosened by weathering (Fig. 30). They consist of angular pieces of rock of varying size, from minute bits to larger blocks whose origin is easily proved not merely by the nature of the deposit, but also by actual observation of the process of its production; for the fall of fragments from the cliff is often seen. Among mountains where

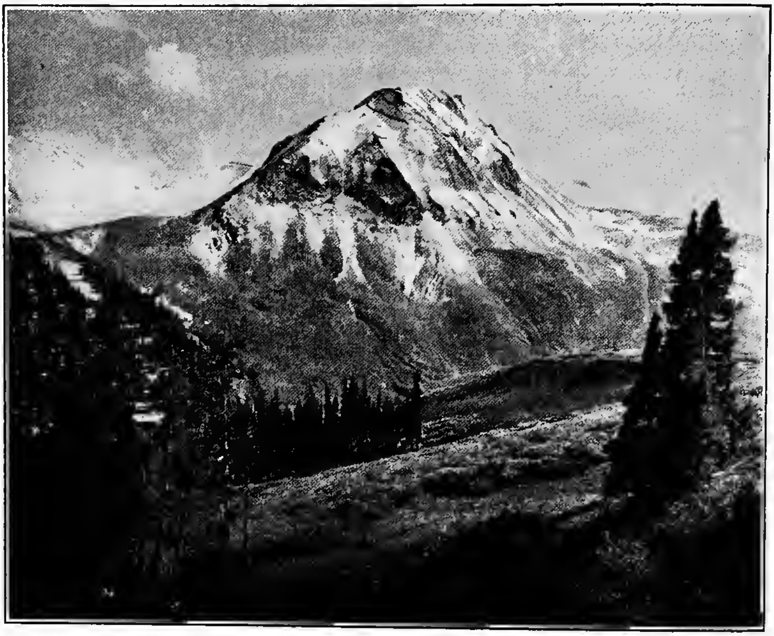


Fig. 30. — Talus slopes in the Rocky Mountains of Colorado. (Cross, U. S. Geol. Survey.)

cliffs are high and weathering active, the rate of talus accumulation is rapid. In the St. Elias Range of Alaska, for instance, every morning for over a week when the sun's rays warmed the surface of a cliff and melted the ice that had formed in the crevices during the preceding night, sharp reports were heard by the author as rock fragments were dislodged, and the falling blocks could be seen descending the talus at the cliff base.

If there is a stream or other transporting agent at the cliff base to remove the talus, its growth is limited, and the excess of supply is taken over by the agent of erosion, and removed to other places. But if there is no such agent of removal, the talus accumulates, forming a curving deposit which slowly rises up the cliff base, protecting it from rapid weathering, and thereby limiting its own supply and growth. Ultimately the upward growth of the talus will reach a balance between supply from above and removal below. Some of the most pleasing curves in mountain topography are those of the talus slope, especially when the supply of rock fragments has become so diminished that vegetation is enabled to clothe it. Above the timber line, and below it wherever the talus supply is rapid enough, the talus slopes are almost, if not quite, free from vegetation cover. They often attain the slope of loose rock fragments at rest, up which it is difficult to climb, and on which one may start a boulder rolling whose motion sets up a sliding of an extensive area of unstable talus.

Deposits due to Creep. — Even on slopes so gentle that the mantle rock is able to completely cover them, there is a downhill movement of rock fragments, often so slow that it cannot be observed, though its effects are noticeable. This movement, called *creep* or soil flow — *solifluction* — is determined primarily by gravity, though it is aided by percolating water, which lubricates the particles and, therefore, makes slipping more easy. By slow creep (Fig. 31), the mantle rock is steadily moving from higher to lower positions, and this is one of the reasons why the layer of disintegrated rock is commonly thicker at hill base than on hill slope and hill side. As a result of creep, trees growing on hill slopes are sometimes inclined because of downhill movement, and the layers of the bed-rock over which the creep has passed are bent down hill. Creep, though so slow as to escape casual observation, is so widespread and so continuous that it is to be reckoned as one of the leading causes for the removal of rock waste. Although far less spectacular, creep is probably much more important as a general agent of removal of disintegrated rock than talus formation, which is confined to the relatively rare areas of cliff outcrop.

Creep is closely related to talus formation in that it is dependent primarily upon the downhill pull of gravity; and in a sense it might be considered the analogue of talus development upon gentler slopes. It is, however, a more complex process, for, besides mere gravity pull upon previously disintegrated rock fragments, there is the action of percolating water and rain wash, thawing and freezing, expansion and contraction with change of temperature, and the push of the wind, especially on tree-covered slopes. All these causes coöperate to aid gravity in its task of drawing the loose fragments down the gentle slopes.

Avalanches and Landslides. — A third expression of gravity work upon more or less completely weathered rock is the occasional fall of large masses of rock, called *avalanches* or *landslides*. This is especially common in lofty mountains, though observed on lesser scale in regions of gentler slopes. There is every gradation from the loosening and falling of a small piece of rock from a cliff to a huge landslide involving hundreds of cubic yards of rock and earth. Here, as in so many other

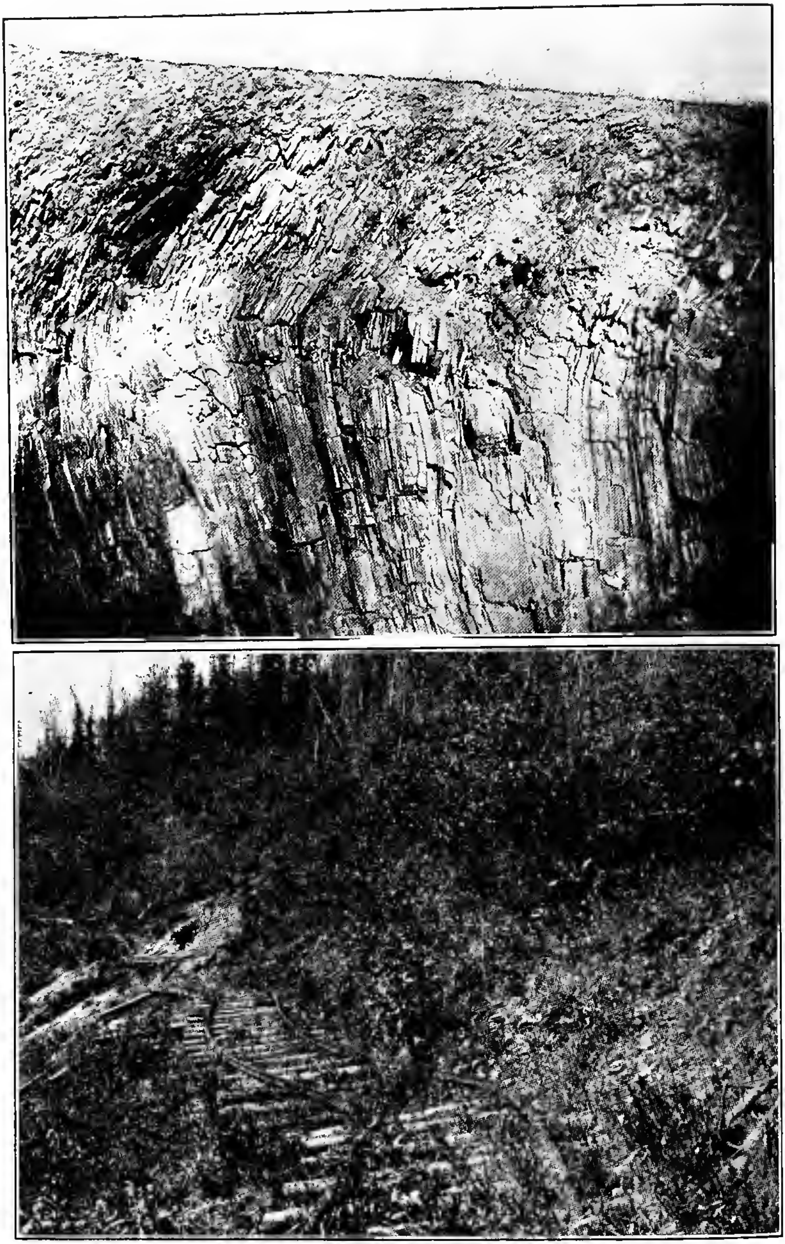


FIG. 31. — Features due to creep. Upper view (Hardin) shows rock layers bent down hill in Pennsylvania. Lower view (Atwood, U. S. Geol. Survey) shows the displacement of a railway by hillside creep near the Yukon River.

phenomena of the earth's surface, however, the same phenomenon may result from more than one cause. Landslides, for example, may be started by the undermining action of a stream flowing at a cliff base; or by the ocean waves cutting back at the base of a sea cliff; or by a glacier steepening a valley slope by its erosive action; or by underground water dissolving out a cavern whose roof falls in; or the lubricating effect of water percolating along planes of easy passage in the strata, or even by man in mining at the base of a cliff. It is not always easy to tell the exact cause by which sufficient instability was given a slope to permit its avalanching to lower levels, and often it is apparently the result of more than a single cause.

Whether due to weathering or to other cause, landslides in general may be considered a part of that disintegration by which the rocks are being reduced to fragmental condition. In many landslides, and if the smaller ones are included, in the vast majority, the primary causes for the downfall are weathering and the pull of gravity. On steep valley sides in mountain regions, weathering has opened up joint planes and other cavities, into which water finds its way, to carry the work further either in the form of frost or of underground water. Ultimately a part of the steep valley wall becomes so unstable that gravity pulls it down, though it sometimes happens that the final cause for movement is the pressure of a strong wind or the weight of a heavy snowfall, or the melting out of the frost, or the vigorous shaking of an earthquake. In all cases the landslide is the final descent of a mass of earth or rock which, through previous preparation, has been given so unstable a condition that it can no longer remain there. Among the agents of preparation, weathering is one of the most effective and is, therefore, to be considered as one of the landslide causes. The fall of the landslide itself is to be classed as a part of the process of weathering from another point of view, since by it, whatever the cause, the process of weathering is thereby aided by exposure of fresh rock to the air and percolating water.

While landslides are common and spectacular phenomena, and the underlying causes are several and widespread, they are not among the leading phenomena of denudation, for they can develop only under exceptional conditions, and after a long period of preparation. For example, in Quebec, a cliff separates the upper and lower town. For several centuries the houses of the lower town extended up to the cliff base, and upon the cliff crest rested the fortifications, but in 1800 a mass of rock slipped away from the cliff face beneath the citadel, overwhelming houses upon which it was avalanched. Several centuries had been required for the preparation necessary for this landslide. A similar conclusion is to be drawn from the landslide which descended the steep mountain slope at Amalfi in Italy, removing rock from beneath one end of the old monastery which had stood there for seven or eight centuries.

When vigorous earthquakes occur, unstable conditions which ultimately would express themselves in landslides are discovered, and in a few minutes numerous landslides are precipitated, which under normal conditions would descend one by one whenever the degree of instability became sufficient for gravity to act.

In the Canadian Rockies a tremendous rock mass nearly half a mile square fell from a mountain side in 1903, partly destroying the town of Frank, Alberta, and killing about 70 persons. The landslide completely crossed a broad valley and partly ascended the opposite slope, burying nearly a mile and a half of railway and producing a new configuration of the earth's surface, the *landslide topography* shown in Pl. I and Figs. 32, 33. Gravity, aided by man's activity in mining in

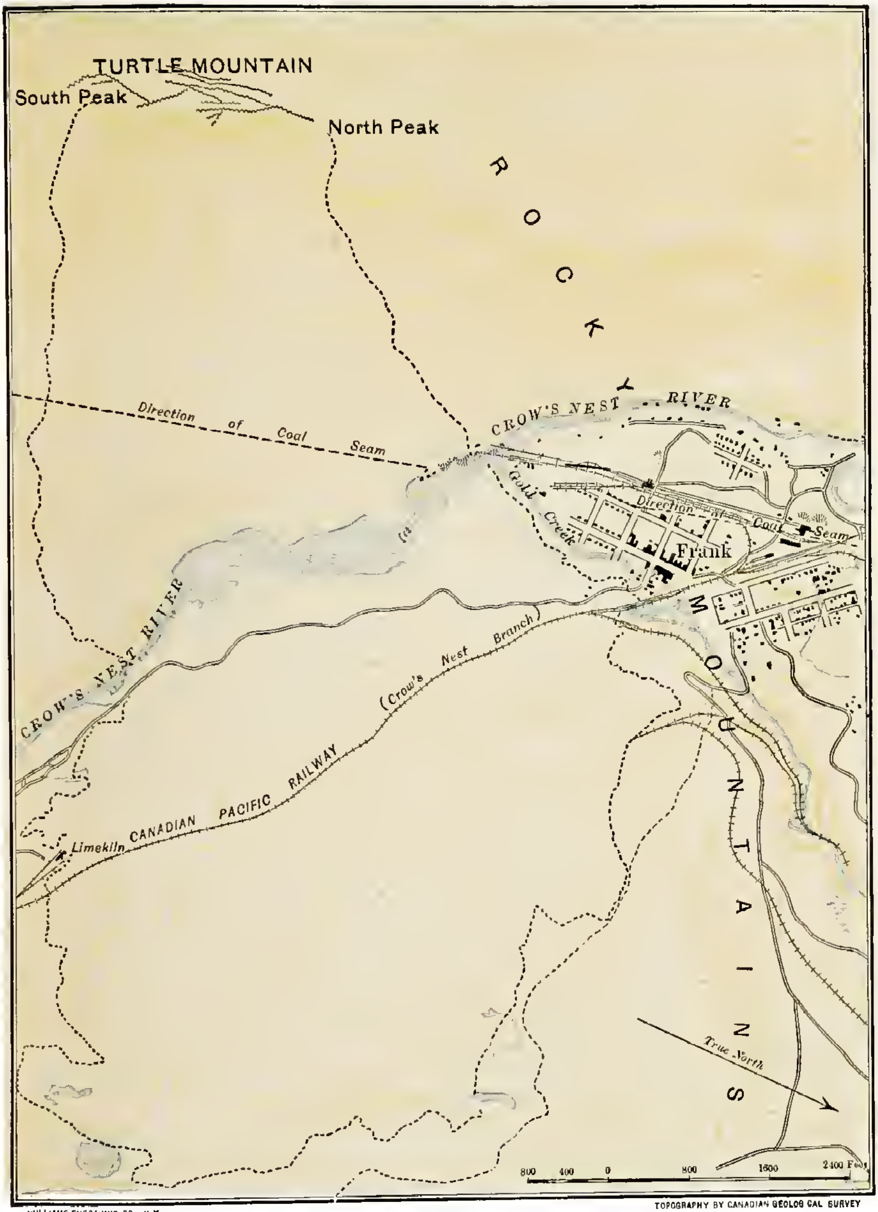
FIG. 32. — View of the Frank landslide. (Canadian Geological Survey.)

the mountain, in combination with certain natural features of topography and structure, caused this landslide. The adjacent peaks were so weakened that gaping cracks are now visible on the mountain side, and it is quite within the realms of probability that another landslide may take place. It would be most wise to move the town because of this danger.

This is one of the largest landslides in the world. It brought down nearly as much rocky material as that of Rossberg in Switzerland, and many times as much as the Elm landslide of 1881 and the Simplon avalanche of 1901. The Rossberg landslide in 1806 resulted in the destruction of four villages and the loss of 457 lives.

The Formation of Soil

The Importance of Soils. — Among the results of weathering the formation of soil is to be classed as by far the most important from the human standpoint, for it is this softening and preparation of solid rock that makes possible the varied and extensive development of



TURTLE MOUNTAIN, AND FRANK, ALBERTA

A landslide came from the area on Turtle Mountain between the North and South Peaks in 1903. It spread across the valley within the limits of the heavy dotted line. Contour interval 20 feet.

life on the lands. The soil, together with the underlying subsoil, is the most extensive and widespread of all the deposits directly due to weathering (Fig. 34). It is that part of the disintegrated rock which remains at or near the source, — the excess of supply over removal.

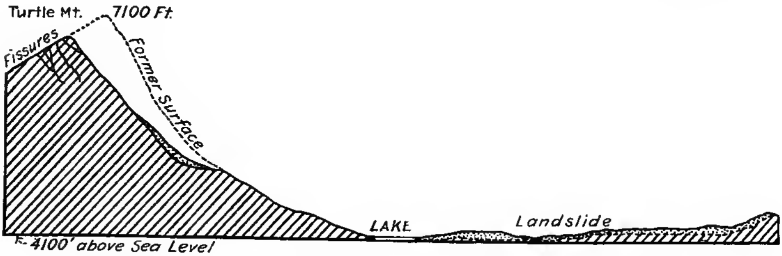


FIG. 33. — Cross section showing the Frank landslide. (After McConnell and Brock.)

Limestone Soils. — In the Bermuda Islands, there is a thin, bright red soil, absent on many of the slopes, but often fairly deep in the depressions. It rests directly on the white limestone, forming so striking a contrast to it, both in colour and texture, that it was once thought to be an ocean bottom deposit. This soil has been derived from the slow wasting away of the white limestone, which is composed of grains of coral and shell. As the rain-water has fallen on and percolated into this limestone, it has dissolved and carried off the carbonate of lime of the coral and shells; but in these are certain foreign sub-

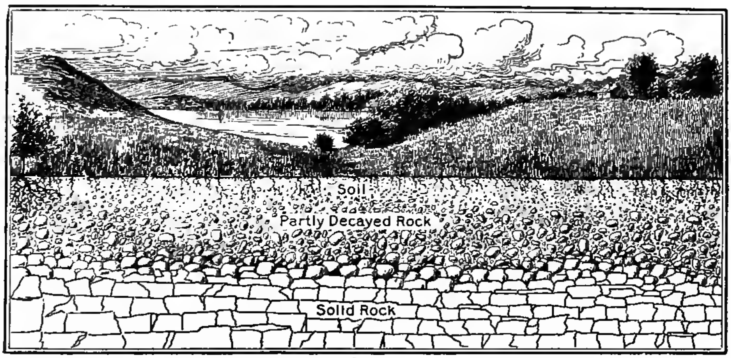


FIG. 34. — The gradation from solid rock to partly decayed rock and residual soil.

stances not so easily dissolved, such as silica and salts of iron, and these have remained as a residue, which, being minute in quantity, has given rise to only a thin soil cover whose red colour is due to the presence of iron oxides. Such a soil is called a *residual soil*, being the residue left by weathering.

Since limestone consists in the main of soluble minerals, the soil that results from its disintegration by the agents of weathering is commonly thin, for, even though it may be rapidly disintegrated, the residue that remains cannot be great in quantity. Moreover, since it consists in the main of minute impurities in the limestone, the texture is so fine that it is easily moved by the agents of erosion.

Granite Soils. — Rocks of more complex composition tend to leave a much deeper and more varied product on disintegration. Granite, for example, consists of quartz, which is only slightly soluble, and which resists chemical change, and of feldspar, hornblende, and perhaps other minerals. The latter are insoluble, but their decay gives rise to fine-textured products, some of which are soluble, some insoluble. Thus a residual soil derived from the disintegration of granite varies in texture, containing grains of quartz and clay, side by side; and the residue from the disintegration of a given thickness of granite is many times greater than that from limestone of the same thickness. Even in the case of soil produced from granite, however, there is some removal of soluble parts, so that the disintegrated product is much less in amount than the bulk of the rock from which it was derived.

Variations of Soils. — All rocks being subject to disintegration, the formation of residual soil can result from the action of weathering upon any kind of rock; and since rocks vary in mineral composition the resulting soil naturally varies both in texture and composition, according to the kind of rock from which it is derived. In the soil itself, that is, the upper layer of mantle rock, these differences in texture and composition tend to disappear under the continued comminution to which they are subjected by the action of plants, animals, and percolating water. The soils of different origins still further tend toward uniformity by reason of the admixture of organic materials, which commonly amounts to six or eight per cent of the whole, and in places to far more, notably in swampy areas. Yet there are notable differences among residual soils, some being coarse, others fine, in texture, some sterile, others fertile. For instance, in the Blue Grass region of Kentucky the soil derived from limestone containing phosphatic shells is so fertile as to give the basis for a special agricultural industry, whereas round about it are areas of infertile soil derived from other rocks and hence sparsely settled and of little agricultural value.

Soil, Subsoil, and Weathered Rock. — The soil proper is only the upper portion of the disintegrated rock, in which there is an appreciable admixture of organic matter. It varies in depth from a few inches to two or three feet. The soil grades downward into the subsoil, which is ordinarily less comminuted, and in which there is little or no organic matter. The depth of the subsoil varies greatly, but in regions where it is derived by rock disintegration it is not commonly more than a score or two of feet in depth, and often much less. It grades imperceptibly into the rock bed from which it is derived (Fig.

34), and the line of division between subsoil and bed rock is ordinarily difficult to draw and very irregular, for the zone of decay extends deeper in some places than in others. Where joint planes offer paths of entrance to percolating water, or where easily disintegrated rock layers occur, the zone of decay descends farther into the bed rock than in the intermediate areas of better resistance.

At and near the bed-rock surface, unconsumed remnants of the decaying rock exist as rounded boulders embedded in the disintegrated material. Percolating water, passing along joint planes and bedding planes, has decayed the rock on either side of the planes, and has eaten into the rock at the angles where these planes meet, thus rounding off the angles. But decay has not penetrated to the heart of the hard rock, and the core remaining is often quite fresh, though completely surrounded by disintegrated rock. When the products of disintegration are removed, as by wind or running water, these undecayed remnants stand out upon the surface as rounded boulders.

Thinness of Soils. — Gravity prevents the accumulation of disintegrated rocks upon steep slopes, and by creep it tends also to cause the mantle rock to move away from even lesser slopes. Rain wash, wind action, and other agents of erosion tend also to carry away the unconsolidated rock, while percolating water is steadily engaged in removing soluble constituents. It is as a result of these movements that the thickness of the mantle rock is kept down to the present limits, for although it is always forming, it is also always moving away from the place of origin. That which remains represents merely the excess of formation over removal. Much of that which is removed finds temporary accumulation on the lesser slopes, and there it may attain depths of several hundred feet; but far more of it finds its way into the streams and is borne far away.

Transported Soils. — Some of the rock material thus transported finds lodgment on the land, there giving rise to soil far from the source of its origin. Such are wind-blown deposits, and river deposits on floodplains and deltas. These are *transported* soils, for although their component parts may have been originally derived by weathering, they owe their present position, texture, and composition largely, if not entirely, to the agent of transportation. Among transported soils some of the most important are those that have been brought to their place of deposit by glacial action. The soils of a large part of densely settled northwestern Europe and northeastern North America are of this origin. Transported soils differ from residual soils in having no necessary relation to the rock upon which they lie, and in resting upon this rock with an abrupt boundary (Fig. 176) instead of grading into the bed rock.

Soil the Basis of Agriculture. — Whether transported or residual in origin, the soil as the seat of plant growth is of vital interest to man; for it contains mineral substances which he needs, and the plants have developed the power of abstracting these from the soil and transforming them to a condition in which they can be incorporated into the human body. For the utilization of the mineral substances the first step must needs be the crumbling of the hard rock under the processes of weathering, then the intervention of plants that find a foothold in the soil.

References to Literature

J. G. Andersson. Solifluction, a Component of Subaerial Denudation, Journ. Geol., Vol. 14, 1906, pp. 91–112.

J. C. Branner. Ants as Geological Agents in the Tropics, Journ. Geol., Vol. 8, 1900, pp. 151–153; Geological Work of Ants in Tropical America, Bull. Geol. Soc. Amer., Vol. 21, 1910, pp. 449–496; Decomposition of Rocks in Brazil, *ibid.*, Vol. 7, 1896, pp. 255–314; Bacteria and the Decomposition of Rocks, Amer. Journ. Sci., 4th series, Vol. 3, 1897, pp. 438–442.

A. P. Brigham. A Norwegian Landslip, Bull. Geog. Soc. Philadelphia, Vol. 4, 1906, pp. 292–296.

H. O. Buckman. The Chemical and Physical Processes Involved in the Formation of Residual Clay, Trans. Amer. Ceramic Soc., Vol. 13, 1911, pp. 336–384.

Charles Darwin. The Formation of Vegetable Mould, New York, 1883.

C. Davison. On the Amount of Sand Brought up by Lobworms to the Surface, Geol. Mag., new series, Vol. 8, 1891, pp. 489–493.

O. A. Derby. Decomposition of Rocks in Brazil, Journ. Geol., Vol. 4, 1896, pp. 529–540.

A. Geikie. Rock-Weathering Measured by the Decay of Tombstones, Geological Sketches, London, 1882, pp. 159–179.

Albert Heim. Über Bergsturze, Zurich, 1882; Der Bergsturz von Elm, Zeitschrift der Deutschen Geol. Gesell., Vol. 34, 1882, pp. 74, 435–439.

E. W. Hilgard. Soils, New York, 1906.

C. G. Hopkins. Soil Fertility and Permanent Agriculture, Boston, 1910.

E. Howe. Landslides in the San Juan Mountains, Colorado, Prof. Paper 67, U. S. Geol. Survey, 1909, pp. 1–55.

A. A. Julien. On the Geological Action of the Humus Acids, Proc. Amer. Assoc. Adv. Sci., Vol. 28, 1880, pp. 311–410.

F. H. King. The Soil, New York, 1895.

R. G. McConnell and R. W. Brock. Report on the Great Landslide at Frank, Alberta, Appendix to Part 8, Ann. Rept. Dept. Int. of Canada for 1902–1903, Ottawa, 1904, 17 pp.; see also **R. A. Daly, W. G. Miller, and G. S. Rice**, Memoir 27, Dept. of Mines, Geol. Survey Branch, Ottawa, 1912, 34 pp.

G. P. Merrill. Rocks, Rock Weathering, and Soils, New York, 1897; Principles of Rock Weathering, Journ. Geol., Vol. 3, 1896, pp. 704–724, 850–871.

A. Penck and Others. Papers on soil flow in Spitzbergen, Iceland, and Central Europe. Zeitschrift Gesell. Erdkunde zu Berlin, 1912, pp. 241–270.

I. C. Russell. Subaerial Decay of Rocks, and Origin of Red Color of Certain Formations, Bull. 52, U. S. Geol. Survey, 1889, pp. 1–65.

N. S. Shaler. Origin and Nature of Soils, 12th Ann. Rept., U. S. Geol. Survey, Part 1, 1891, pp. 213–345.

R. S. Tarr. The Relation of the Secular Decay of Rocks to the Formation of Sediments, Amer. Geol., Vol. 10, 1892, pp. 25–44; Rapidity of Weathering and Stream Erosion in the Arctic Latitudes, *ibid.*, Vol. 19, 1897, pp. 131–136.

C. R. Van Hise. The Belt of Weathering, A Treatise on Metamorphism, Monograph 47, U. S. Geol. Survey, 1904, pp. 409–561.

T. L. Watson. Weathering of Granitic Rocks in Georgia, Bull. Geol. Soc. Amer., Vol. 12, 1901, pp. 93–108.

CHAPTER III

THE WORK OF WINDS

Activities of the Wind

We have seen that the atmosphere is directly and indirectly an aid to rock disintegration in the complex process of weathering. It is a potent agent of change on the earth's surface in other directions also, primarily through its movements which we call winds. Some of the most important effects of the winds are indirect, as in influencing temperature, in transporting water vapour, and in causing waves and currents in lakes and oceans. But the winds are of importance in a direct way, by their own work upon the surface of the lands, and it is this phase of the subject with which we are now concerned.

The wind is one of the agents of erosion, which means that it is engaged in removing, transporting, and depositing rock fragments. Wind erosion is operating with greater or less effectiveness in all climates and regions, but it is least effective in humid lands, especially where clothed with vegetation. There are four different types of land surface on which wind erosion is most active: (*a*) humid lands, (*b*) lofty mountain tops, (*c*) portions of the narrow strip of sea coast, (*d*) arid lands and deserts, the most extensive and important of all. These four different types of land surface will be considered separately, beginning with the humid lands.

Wind Work in Humid Lands

Relation to Vegetation. — Where vegetation densely clothes the land, the loose, disintegrated rock is held in place and protected. Yet even here, strong winds now and then overturn trees, and winds of hurricane force, such as accompany tornadoes, may plough a path through the forest, even carrying the trees away bodily. The overturning of the trees moves rock fragments a short distance, and, in the upturned roots, exposes soil or stone to the agents of weathering, but this is a minute effect.

Aid from Man's Activities. — By his occupation of humid lands, man has created opportunity for the operation of the erosive work of the winds by the removal of the forest, and by exposing the soil in roads and ploughed fields. That this opportunity is taken advantage of is easy to see when gusts raise clouds of dust from field or road, and whirl it away.

Dust in the Air. — Even with the aid of man, however, the erosive work of the wind in humid regions has not become an agent of great change. It is, nevertheless, an effective agent of deposition, even in humid lands, for dust is ever present in the air and ever settling from it. Derived at some favourable point, minute fragments of minerals, together with other solid impurities, may be floated in the air for days and even months before settling to the earth in a place far distant from their source. Sometimes this dust slowly settles in days of calms, sometimes it is brought down in the raindrops and snowflakes, but more rises to take its place, buoyed up by the variable currents of the air. The heavy, hazy atmosphere common during periods of dryness is due to dust, of which mineral particles form a portion, and the cleanness of the air after rain is the result of temporary removal of the solid impurities by the falling rain.

At times the fall of dust from the air is so noticeable as to attract widespread attention. For example, dust clouds and dust storms whose source is apparently the distant Sahara are occasionally observed in Italy and southern France; and sometimes the rain is coloured red from the abundance of reddish mineral matter, giving rise to what is known as "blood-rain."

Dust from Volcanic Eruptions. — Another source of mineral dust in the air is from volcanic eruptions. Volcanic ash erupted from Vesuvius has fallen in Constantinople; ash from Icelandic eruptions has fallen in Scandinavia; and the ash thrown into the air by the great eruption of Krakatoa in the Straits of Sunda, in 1883, spread far and wide over the earth, and in such quantities as to cause brilliant sunsets in Europe and America months after the eruption.

Dust Settling from the Air. — From volcanic sources, from exposed surfaces in humid lands, from mountain tops, and from arid lands mineral dust is rising into the air, where it floats about, together with smoke particles and other foreign substances. Carried far and wide by the winds, this material returns to the earth on sea and land, in humid and arid regions. How important this supply of wind-drifted dust is, in humid lands in general, we are not in a position to say, though when considered as a process continuing through thousands of centuries it seems probable that its result has been noteworthy. Near the borders of arid lands, where there is much fine material within easy reach of winds from such regions, the importance of the fall of dust upon the land is certainly great. It is doubtless one of the important factors involved in the burial of the monuments of the ancient Roman civilization. That this is not an improbable statement is indicated by the fact that an inch of dust is reported to have fallen in parts of Italy during a single dust storm.

Wind Work on Mountains

Lofty mountains are exposed to strong winds, for they rise into the rapidly moving, upper air currents. These winds readily move light materials, such as snow and mineral fragments, and in exposed places are, therefore, of importance in checking the accumulation of a protective cover on the bed rock. The work of the wind is aided by the general absence of vegetation and by the steep slopes, both of which leave surfaces exposed to its action. As soon as a grain of mineral is loosened from a rock surface by weathering, and even before it is ready to fall away under the pull of gravity, the wind at exposed points is present to carry it away. Even particles of rock larger than sand grains may be carried by violent winds, and whirled with such force as to strike a painful blow on the face and hands.

We have no measurements for the determination of the rate of work of the wind in such situations, and it would be difficult to measure in any event, since it is but one of several processes which are at work reducing mountain elevations and since its work is irregularly distributed. But to one who has been much on the windward side of peaks, and in certain passes through which the wind persistently sweeps, the direct attack of the wind is one of the significant factors of denudation.

Bearing upon this point is the evidence from the deposit of wind-drifted dust upon glacier surfaces and upon snow fields. In Greenland, for example, at a distance of several miles from the nearest land, dust is present on the glacier surface in such quantities that, gathering in little depressions, it forms dark-coloured deposits. By absorption of heat these melt holes in the ice, called dust wells, in the bottom of which the dust deposit stands. Some of this dust collected by the author and examined under the microscope was found to contain mineral fragments like those of the nearest mountains. A similar phenomenon has been observed in Spitzbergen and in Alaska.

Wind Work along Shorelines

Portions of the sea coast are especially favourable to effective wind work, for there are three favouring conditions: (*a*) an abundance of sand thrown up by the waves, (*b*) absence or sparseness of vegetation because of the porous sandy soil, its frequent movement, and the unfavourable effect of the salt spray and water, (*c*) the rapid drying out of the loose sand both between tides and in the zone above ordinary wave reach. All of these conditions, excepting the influence of the tides and of salt, may be found also on lake shores.

The Formation of Sand Dunes. — With an abundant supply of dry sand, having little or no vegetation to hold it in place, the wind readily moves the sand before it, sometimes lifting it well above the surface, but more commonly drifting it along with the accompanying development of ripple marks (Fig. 35). Closely examined, the movement is seen to consist of a motion of the surface film of sand, rising up one slope of the ripple mark and dropping down over the other slope (Fig. 39), so that the ripple itself is constantly changing form and position. These sand movements are most effective under the influence of drying winds, which need not necessarily be very strong; but unless it is very wet, even damp winds cause the sand to drift, though in this case the wind force must be strong. Very violent winds whirl the sand before them, and are even able to pick up and transport shells and shell fragments.

The sand is drifted in any direction that the wind may happen to be blowing, but since the great majority of winds blow either on shore or off shore, either directly or diagonally, the chief sand movements are either landward or seaward. In the latter case the sand comes within the reach of the waves to be thrown back again; but in the former it accumulates on the land back of the beach. Here the ten-

FIG. 35.—The checking of sand dune movement by vegetation on the coast of New Jersey. Ripple marks on the sand.

dency is for it to form a narrow strip of low sand hills, called *sand dunes*, whose width and height depend upon the extent of the land supply, and the force, direction, and dryness of the wind. Very often the dune strip is but a few yards wide, but in some cases it attains a width of several hundred yards, and even a mile or several miles. On the seaward side the dune face is fairly steep, due to the occasional attack of the waves at its base; on the landward side it grades downward through lower and lower hills to a thin film of sand, or, if there is a lagoon behind the dune area, the sand grades into lagoon bottom sediments. In their highest portion the dunes are commonly not more than 50 or 75 feet, and often much less, but they may reach heights of 200 or 300 feet.

The reason why the sand dunes are commonly highest near the beach is, first, the nearness to abundant supply, and, secondly, the effect of sand-loving vegetation (Fig. 35) in checking the movement near the source of supply. The sand dunes have a very irregular form, though normally consisting of low, short ridges, or oval hills, with basin depressions between. Ordinarily they are subject to frequent, or even constant, change in form and size, for as the wind direction or force varies, deposition occurs at one time and removal at another. The sand layers which are thus deposited, partly removed, and then covered with other layers, assume various angles according to the slope on which they lie, and various positions with relation to one another. This gives rise to a cross-bedded structure known as *wind-drift-structure*, which is characteristic of wind-drifted sand deposits.

Erosive Work. — As viscosity protects the sand grains it seems improbable that grains less than 0.755 millimetre could be well rounded under water; when the sand leaves a beach, however, and is moved about by the wind the grains are ground together and reduced in size by slow attrition; but little erosion is performed here by sand driven against the hard rock, because, ordinarily, there is little if any such rock in the sand dune areas. Here and there, however, there are rock cliffs at beach ends, and here the rock is polished and worn by the sand blast. That the driving of sand against rock may be an efficient agent of erosion is indicated by the fact that an artificial sand blast is employed in chipping away the surface of glass in the process of manufacturing ground glass. On the island of Monomoy, south of Cape Cod, the glass in a window in a fisherman's house was so chipped by the natural sand blast that objects outside could be seen only indistinctly, and the fisherman told the author that it had been done in a period of twelve years.

Encroachment of Dune Areas. — The movement in sand dunes is often very rapid, the complete form of a dune being changed during a wind of a few hours' duration. As the sand drifts about, it collects in lee spots, much as drifting snow does, and it is often necessary for a man living in a sand dune area to keep a path shoveled from his house door through the sand, just as, in winter, a path must be shovelled through the snow. The lighthouse-keeper at Ipswich, Mass., has a raised wooden walk from his house to the lighthouse, but, even from this, the sand must be shovelled away frequently.

Even the dune area itself may migrate or extend its limits, usually when there has been some interference with natural conditions. This is well illustrated by the change at Coffin's Beach on Cape Ann in Massachusetts. Here, at the close of the eighteenth century, there was a broad sand beach facing westward, and backed by the normal fringe of sand dunes, behind which stood a farm and behind that the virgin forest. The owner of the farm stripped off the forest, and the sand began to move, inundating his farm with a flood of drifting sand, which to this day has not ceased its movement.

On the coast of Europe there are numerous cases of the landward advance of sand dune areas. Around parts of the coast of the Bay of Biscay, for instance, the sand has marched inland at the rate of 16½ feet per year. In their advance the dunes have overwhelmed farms, houses, and even villages; and in some cases in their onward march these buried places have been partly or wholly uncovered (Fig. 36). The advancing sand encroaches upon forests, partly or completely burying the trees, then, with further changes, uncovering them again. Where the wind direction, supply, and topography are favourable the march of drifting sand is irresistible and overwhelming, carrying complete disaster with it.

Yet in places it is possible to check or retard the destructive advance. This may be done, for example, by establishing a forest windbreak in the rear of the dune area, or by planting trees, shrubs, or grasses that can grow in such a soil. European governments have

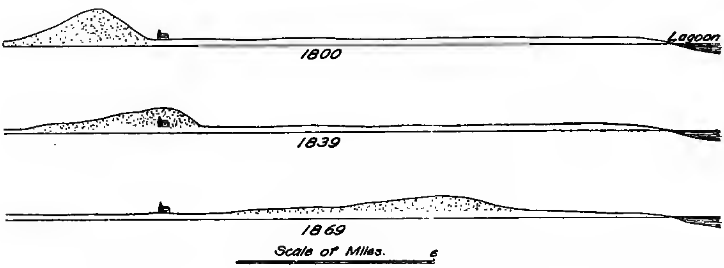


FIG. 36. — Burial and uncovering of a village in northern Germany by sand dunes. (After Behrendt.)

done much to check the movements of the drifting sands, and latterly the United States Department of Agriculture has been doing a valuable work in this direction, experimenting with different kinds of plants adapted to growth in the sand (Fig. 35) and with other means of holding the sand in place and protecting contiguous areas from its encroachment.

Settlement of Dune Areas. — Most coastal sand dunes are composed of quartz sand, the material of the beaches, and they are, therefore, barren areas, for neither wild nor cultivated plants take kindly to such a soil. Ordinarily, therefore, the settlement of sand dune areas is sparse, and the inhabitants are mainly scattered fishermen, light-house-keepers, and others whose livelihood is connected with the sea rather than the land. Where the movement of the sand has nearly or quite ceased, the dunes may support a sparse pine or other forest; and some dunes whose composition is of other than quartz fragments may have a considerable degree of fertility. Instances of such dunes are those in which fine-grained river sediment is incorporated, or those made of shell and coral sand, like the Bermudas.

Aid of Wind in Formation of Sand Bars. — Coastal sand dune areas are widely distributed along ocean shores, and they are not uncommon along lake shores, especially those of large lakes. There is, for instance, an extensive area of this sort, in Indiana, at the head of Lake Michigan in which there are interesting conditions of encroachment upon contiguous forest. From New York southward to Mexico the coast line is fringed for much of the distance by sand beaches with associated sand dunes; and north of New York there are local dune areas, the most extensive being on Cape Cod. Sand dunes are also accompanying features of sandy coasts in other parts of the world.

The sand dune strip is a prominent part of many sand bars and low sand islands immediately off shore from the mainland. The waves throw the sand up to the limit of their highest reach, and the wind then piles the sand higher, raising the bars and islands and broadening them, thus making habitable land, free from danger of inundation by the sea. The growth of these sand bars and sand dunes sometimes partly encloses lagoons, and diverts the land drainage, deflecting the stream mouths by forcing them to seek outlet around the end of the bar. Locally areas are completely shut in by the growth of the dune areas, giving rise to broad depressions and to ponds and small lakes. Still another effect is to act as a breakwater to protect the low-lying mainland behind from the attack of the ocean waves. A considerable part of the coast of Holland is efficiently protected in this way.

Aid of Wind in Formation of Islands. — Many oceanic islands owe a part, if not all, of their area and height above sea level to the wind action. This finds illustration in the Bermuda Islands. Here lime-secreting animals thrive upon a submarine platform, whose foundation is probably a volcanic cone rising from deep water nearly to sea level. By their life and death these animals supply material, mainly corals and shells, for the waves to accumulate and grind up on beaches, forming coral and shell sand. This loose sand is drifted before the wind and has been piled up into an extensive sand dune area with the hillock and basin topography and the typical wind-drift-structure. The highest point to which the coral sand has been carried is about 250 feet above present sea level.

The formation of the Bermudas, though the work of the past, is not a completed process, for they are still being built up. Coral and shells still thrive on the offshore reefs; beaches of coral and shell sand still exist along the coast; and the wind is still driving the sand inland. At one part of the south coast the sand has encroached upon gardens and fields, and has even overwhelmed and almost completely covered up a native house.

Two conditions are adverse to the rapid shifting of sands here: (1) the fact that numerous plants, notably the oleander, thrive even in the shifting coral and shell sand, soon forming thickets which check its movement, (2) the fact that the rain-water, percolating into the limey sand, dissolves carbonate of lime and deposits it around the grains, soon cementing them so that they resist removal by the wind. When the movement of the sand ceases, cementation soon binds the grains together into a rock which can be used for building.

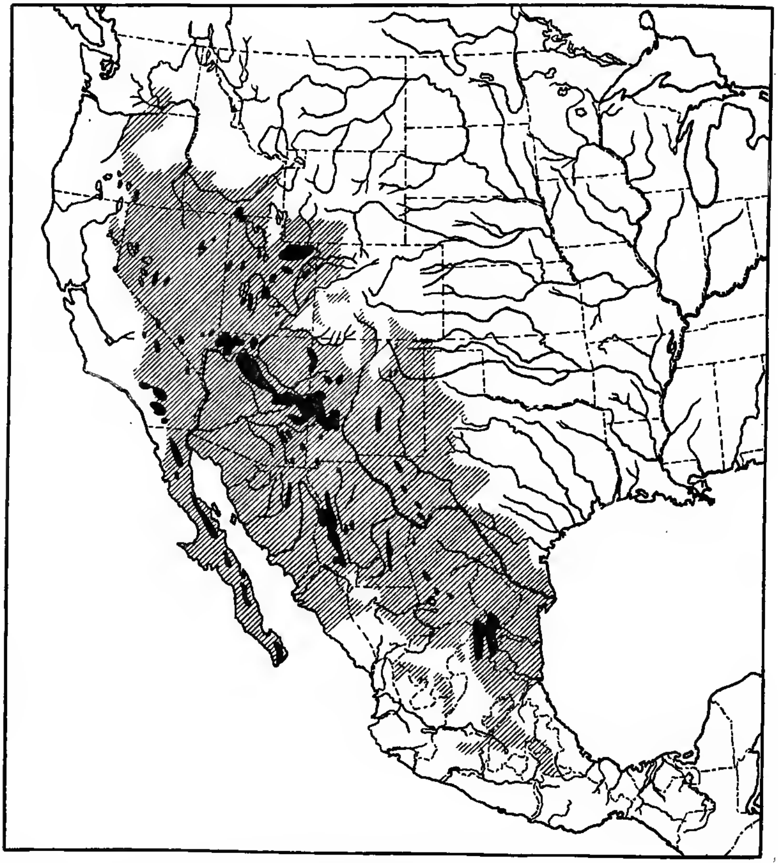


FIG. 37. — Area of North America deserts cross-lined. Black indicates moister mountain areas. (MacDougal and Shreve.)

This process is not confined to the Bermudas, but finds equal illustration in the Bahama Islands, and in many coral islands in the Pacific and Indian oceans. The wind, therefore, is to be reckoned as a potent island builder, taking materials supplied to it by the waves, and raising them above the reach of the sea. Many scores of thousands of people are living upon such wind-built islands.

Wind Work in Arid Countries and Deserts

Extensive areas of the earth have a climate so dry that only sparse vegetation grows, and in some places it is so dry that vegetation is almost absent. Each of the continents has such areas, those in North America lying west of the 100th meridian, mainly in Mexico and western United States (Fig. 37). In such arid regions the soil exposed between the sparse vegetation is almost permanently dry and it is, therefore, subject to transportation by the winds, which are often very strong.

Movement of the Sand. — Normally the loose soil is slowly drifted about, keeping close to the ground, and tending to accumulate around

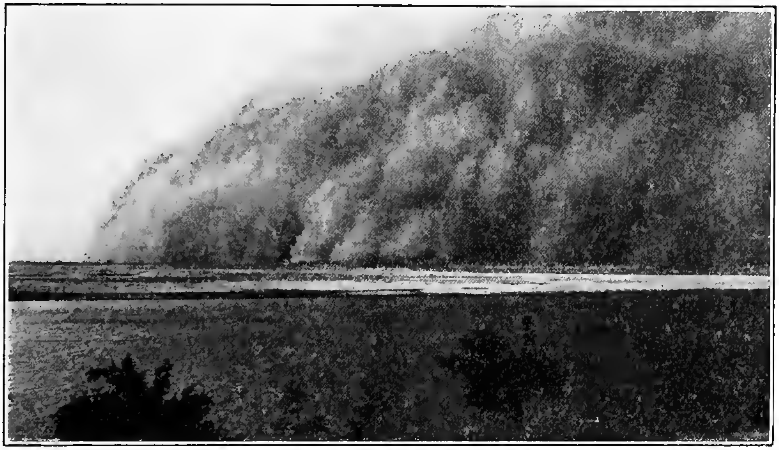


Fig. 38. — Sand storm sweeping over the southeastern part of the Sahara near Khartum in 1906.

obstacles, such as well-rooted plants. The surface is, therefore, made somewhat irregular by many small mounds, out of the top of which one or more plants grow; but the mound is there because of the plant, not the plant because of the mound. This condition decreases toward the border of the arid lands, where, finally, plant growth so covers the surface as to effectively protect the soil from the wind.

Now and then in the drier regions fierce winds sweep over the surface, and then the loose, fine-textured soil is raised in clouds of dust, which so fill the lower air as to completely shut out distant objects from view. In deserts these sand storms assume such proportions as to be dangerous to life, for the air is literally filled with sand, and even breathing is difficult. Extensive deposits are made, the local topography is altered in detail, and paths and trails are obliterated. The sand storm is one of the dreaded dangers of the caravan trade of the Sahara, and is one of the most vivid illustrations of the transporting power of wind when sweeping over desert lands (Fig. 38).

Although more slowly acting, since it is a more continuous process, it is probable that the work of moderate winds is even more potent than that of occasional fierce winds. Still another means of transportation in the arid regions is that of the desert dust whirl. Looking down upon a desert lowland from some neighbouring elevation, one can often see several small columns of dust slowly moving across the lowlands, rising a hundred feet or more in the air with a diameter of but a few feet. These dust whirls develop on hot, calm days by the rising of the heated air, and the rapid inflow of the air, causing a movement of such force as to move along and even lift sticks of wood. Though covering but a small area, the dust whirls are formed so frequently that they are to be reckoned as important agents of transportation, continuing the work of the wind even during periods of calm.

Source of Sand Supply. — It is a common belief that deserts are typically expanses of constantly shifting sand dunes, but this is far from the truth. It is true that over much of the surface there is a drifting of the sand, a rippled sand surface, and the development of mounds around vegetation; and it is true that there are extensive tracts of sand dunes; but there are also bare plateau tops, exposed rock ledges, barren mountain slopes, and fields of stream-borne stones at the mountain base (Fig. 39). The desert is a region of diverse topography and diverse surface conditions, having the one common feature of barrenness (Fig. 41) that aridity brings to all parts of it excepting the scattered watered spots, or oases.

The Growth of Sand Dunes. — Over most, if not the entire, surface of a desert the work of the winds is active, though naturally it varies from time to time and from place to place. Some parts are much exposed to the wind work, while others are more or less protected from it; and some days have little or no wind, while in others the wind blows fiercely. The irregular work of the wind is especially well illustrated by the distribution of the sand dune areas.

These occur only in areas of favourable conditions, notably the presence of abundant supply, of favourable wind direction, and of such protection as to permit the wind to deposit and prevent it from removing the sand as fast as it can be brought. The supply is the prime factor. Material is ready for movement from the barren wind-swept slopes, and from the soil between the scattered plants, and this is being constantly swept about, but it can accumulate in sand dune areas only where some topographic feature intervenes to check its further spread.

By far the most extensive sand dune areas, however, are those with a still more abundant supply, coupled also, at times, with the protective influence of topography. This supply is brought by the streams that here and there flow across the desert or out into it. Many short streams descend from the mountains that border or rise out of desert areas, and there are even some of large volume. As these reach the drier lowlands, their water evaporates and a part or all of the sediment that they bear is left in the dry air at the mercy of the winds. With such an abundant sand supply, extensive tracts of dunes, often scores of miles in breadth, are built, in which the sand rises in a succession of ridges and hummocks with intervening depressions (Fig. 40), across which travel is most difficult and often dangerous. In the dunes the sand is in such constant movement that no vegetation can find a foothold. When the wind blows fiercely, the sand is drifted in blinding sheets, giving rise to the dreaded sand storms. Such sand dune areas are found in all the great deserts of the world, — the Sahara, Gobi, Kalahari, in Australia, the Great Basin and the arid southwestern part of United States (Fig. 37), and many others.

FIG. 39. — Sand dune ridges. (Siebenthal, U. S. Geol. Survey.)

Dunes along Rivers. — Dune areas of similar origin are developed even in semi-arid regions, where stream beds become partly dry during a portion of the year, thus exposing sandy tracts to the wind. Dune areas of this origin are found in western Texas, in the Pecos valley, in the Arkansas valley of western Kansas, in the Platte valley of western Nebraska, along the lower Columbia River, and in many other parts of western North America and other continents. In such places a strip of dune sand of variable width is found on the leeward side of the valley, and often at the base of the valley slope, up which the wind cannot bear great quantities of sand.

Encroachment of the Sand. — The sand dune tracts of arid and desert lands, like those of coast lines, expand in area as the supply continues and thus encroach upon neighbouring land. Ordinarily in desert countries this encroachment is of little importance, because the land is of so little value. But since oases are commonly caused

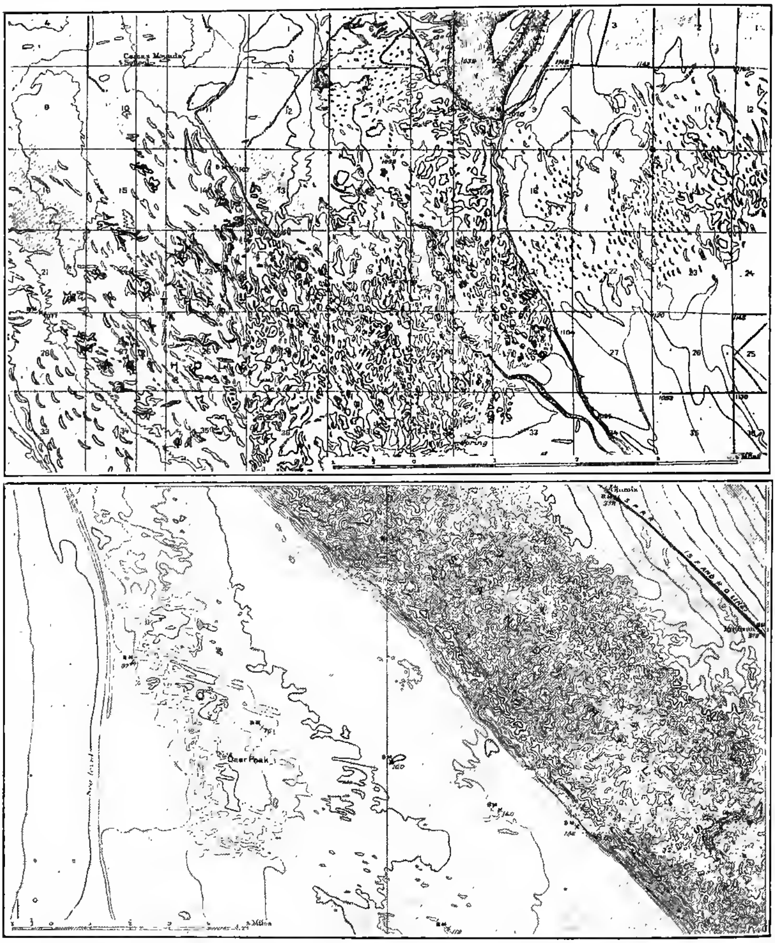


Fig. 40.—Topographic maps of sand dunes in central Washington (upper) and in south-eastern California (lower). (After Moses Lake and Holtville Quadrangles, U. S. Geol. Survey.)

by the water of streams descending from the mountains into the desert, and these streams are the source of the dune supply, it is not uncommonly the case that the sand encroaches upon these valuable, fertile spots, doing much damage. The encroachment of the dunes in semi-arid lands, in which there is often extensive irrigation, is an even more serious matter; and already the problem of checking such encroachment is confronting settlers in western United States, as it has long confronted dwellers in older countries of the Old World.

By the extension of sand dune areas, and by the slower drifting of sand and dust, great changes have been effected in the regions of ancient civilization in northern Africa and the desert and arid portions of Asia. A large part of the débris with which the ancient cities of Nineveh and Babylon are covered is wind-borne dust and sand, and the same is true of many other ruins of western Asia. In Central

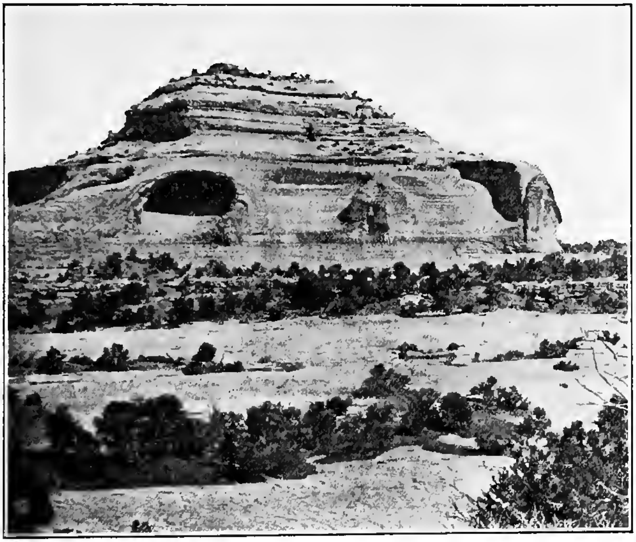


Fig. 41. — Cliff sculptured by the wind in southwestern United States.

Asia there are hundreds of cities buried beneath wind-blown deposits, some of them beneath advancing sand dunes. These and other cases are possibly the result of a change in climate to a condition of greater aridity, thus permitting greater activity of wind action.

Erosive Work in Dry Regions. — The work of winds in arid and desert lands is largely expended upon the transportation of loose, unconsolidated rock fragments, though it is by no means confined to this. As the material is drifted about, it is ground finer, and thus made ready for easier and more distant travel. Even the hard rock itself (Fig. 41) is attacked by the natural sand blast, and the fragments removed add to the supply for transportation. Pebbles and boulders over which the sand drifts are polished, grooved, and faceted by the abrasion of the wind-driven sand to a distinctive shape, the *drikanter;* cliffs are attacked and slowly worn back, the weaker rocks being abraded faster than the resistant ones.

Much of the fantastic sculpturing of rock exposed in desert lands (Fig. 41) is due partly to the erosive action of the natural sand blast. It is, however, difficult to assign an exact value to this agent, since weathering and rain wash are coöperating factors. Yet the fact that such rock forms abound in arid climates, but are rare in humid regions, makes it certain that they are normal products of the agents of denudation in the desert, of which the wind is certainly one of the most important. There seems no escape from the conclusion, therefore, that the wind is a potent agent, even in the destruction of hard rocks, removing by its own force particles already loosened, and, by drifting sand against the rock surface, even scouring off the firmly adhering mineral grains. To the desert the wind as a geological agent is what running water is in humid lands; but whether in general denudation it works more or less rapidly than running water does in humid lands cannot be stated at present. Partly because of the fact that the humid lands are the main seat of human activities, while desert lands are sparsely settled and little known or studied, less is known about the physical geography of the desert, and the agents of change there are but partly understood, and possibly underestimated.

Transportation of Dust out of Deserts. — We have seen that the movement of sand and dust in the desert is almost incessant, and that it gives rise to important changes in and near the area of supply. Much is also borne out of the desert by the winds and allowed to settle on the surrounding regions. By this means the surface of the desert is being slowly lowered.

During violent winds vast quantities of sand and dust are carried into the air. It has been estimated that during a desert storm as much as 126,000 tons of mineral matter may be present in every cubic mile of air. The heaviest of this settles as soon as the velocity of the wind decreases sufficiently, and most of the heavy part finds lodgment in the desert. But the finer dust particle will float in moderately moving air, and thus may not come to rest upon the earth until it has travelled hundreds of miles from its source.

Vessels sailing off the west coast of Africa often experience a fall of dust, which sometimes settles in such amounts that it is necessary to remove it from the decks, and on the Mediterranean it is said to sometimes give the sails of vessels a reddish tint. Dust from the Sahara has fallen on the Canary and Cape Verde Islands, and, as we have already seen, in Italy and southern France. Similar deposits are known around the borders of other desert and arid lands. Such movement of finely comminuted rock material from arid regions is not only an effective cause for the lowering of the surface of such regions, but also of deposition of sediment upon neighbouring lands and seas. Few rivers drain desert lands, and many deserts are closed basins, out of which no water runs. Were it not for the wind, therefore, the disintegrated rock of desert lands would, in the main, accumulate there and fill the basins with a great depth of sandy sediment.

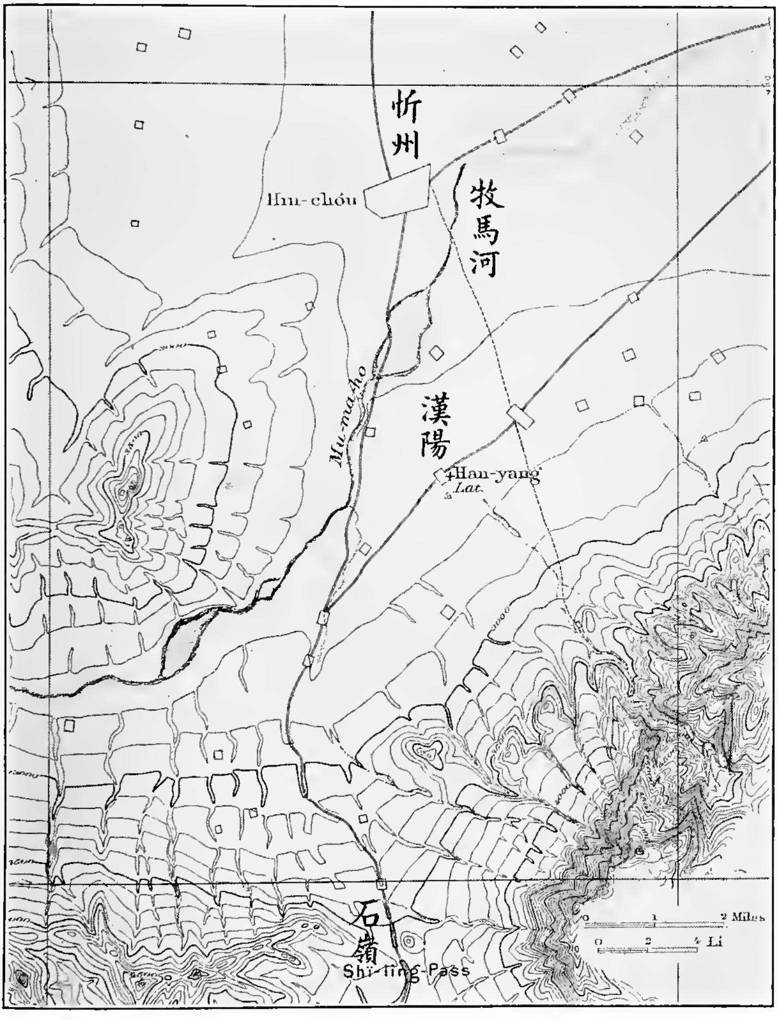


FIG. 42. — Contour map of a loess-filled basin in China. (After Willis and Sargent.)

This tendency is partly counteracted by the action of the wind, which in desert lands is the prime agent, not only of denudation, but of transportation of rock fragments, as rivers are in humid countries.

Formation of Loess. — On lands bordering some of the arid belts of the earth, there are deposits of a fine-grained loam called *loess*, with grains coarser than clay, but finer than sand. A similar deposit is found in some humid lands remote from arid regions, as, for instance, in the Rhine valley, whence the name originally came, and in the Mississippi valley. It is quite probable that deposits of more than one origin are here classified under a single name, based upon physical characteristics, rather than upon origin; but certainly much of the loess and some of the most extensive deposits are of eolian origin.

This is true, for instance, of the vast deposits of loess in parts of China (Fig. 42), where it occurs at elevations up to 5000 feet, and on hills as well as in valleys. It is also true of at least a large part of the extensive loess deposit in central and western United States. Richthofen, as a result of his studies in China, put forward the wind explanation for the remarkable deposit of loess in that country, a theory that has been generally accepted. According to this theory, fine-grained, wind-borne dust, driven from contiguous arid regions, has settled upon the grassy border lands, forming deep deposits, which by the action of rain wash has locally been thickened, especially in the valleys.

Pumpelly proposed an extension of this theory to the loess deposits of the Mississippi valley, and this is now quite generally accepted, though it is also believed that rain wash and sedimentation in quietly and slowly moving waters is the explanation of certain parts of the deposit; and some of the supply may have been derived from the sediments left by the retreating ice sheet of the Glacial Period.

The wind theory receives support from a number of considerations, as follows. The most extensive loess deposits are on or near the border of arid lands and on the side toward which the prevailing winds blow from them. The material of the loess is of such texture as the dust which winds can transport. Both in China and in the United States and Alaska, the process is still in progress. For instance, dust from the plains farther west not infrequently falls in Kansas City; and noticeable quantities of such dust accumulate on the window sills in the central part of Kansas during periods of strong west winds. In the loess are found the remains of plants and animals such as live on the land, and the casts of plant roots extend through the loess. There are other facts also pointing to wind origin, such as the arrangement of the component particles. Altogether, therefore, the wind theory for at least a large part of the loess seems well founded.

Loess and Man. — In the Mississippi valley, the loess is not commonly more than 50 feet in depth, but in China and in the more arid parts of western United States it is from 1500 to 2000 feet in depth in places. It makes a fertile soil and is often the seat of dense agricultural population, where the climate is humid, or where irrigation is possible. In China the thick loess is, in places, much dissected by drainage lines, and the valleys are bordered by steeply rising, often vertical walls, of the unconsolidated loess. These steep walls are the result of the development of vertical cracks, or joint planes in the loess; and the compact, fine-textured loam may remain in the vertical position for a long time. In some parts of China the inhabitants have excavated their houses in the loess slopes, and thousands of Chinese live in such excavations (Fig. 43).

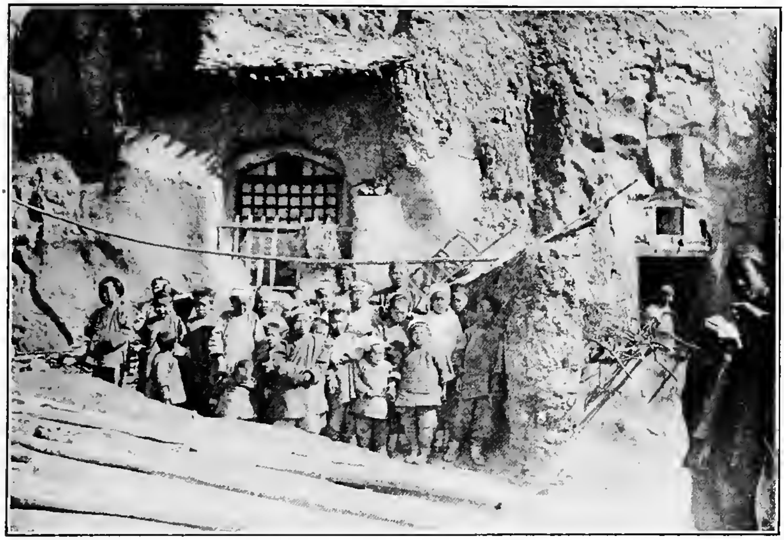


FIG. 43.—A vertical wall of loess in China with excavated dwellings. (G. F. Wright.)

References to Literature

W. P. Blake. On the Grooving and Polishing of Hard Rocks and Minerals by Dry Sand, Amer. Journ. Sci., 2d series, Vol. 20, 1855, pp. 178–181; Explorations and Surveys for a Railroad Route from the Mississippi to the Pacific, Vol. 5, pp. 92, 230; *ibid.*, Appendix to Preliminary Geological Report, House Doc. 129, Washington, 1855, p. 27.

H. J. L. Bradwell. The Sand Dunes of the Libyan Desert, Geog. Journ., Vol. 35, 1910, pp. 379–395.

T. C. Chamberlin. Supplementary Hypothesis Respecting the Origin of the Loess of the Mississippi Valley, Journ. Geol., Vol. 5, 1897, pp. 795–802.

V. Cornish. On the Formation of Sand Dunes, Geog. Journ., Vol. 9, 1897, pp. 278–309.

H. C. Cowles. The Plant Societies of Chicago and Vicinity, Geog. Soc. of Chicago, Bull. 2, 1901, pp. 56–65.

W. Cross. Wind Erosion in the Plateau Country, Bull. Geol. Soc. Amer., Vol. 19, 1908, pp. 53–62.

W. M. Davis. The Geographical Cycle in an Arid Climate, Geographical Essays, Boston, 1909, pp. 296–321.

G. K. Gilbert. Wheeler's Geographical and Geological Surveys West of the

100th Meridian, Engineer Dept., U. S. Army, Vol. 3, Washington, 1875, pp. 82–84, Pls. VIII and IX; Lake Basins Created by Wind Erosion, Journ. Geol., Vol. 3, 1895, pp. 47–49.

Sven Hedin. Scientific Results of a Journey in Central Asia, Stockholm, 1904, Vol. 1, pp. 227–276, 349–369.

A. S. Hitchcock. Controlling Sand Dunes in the United States and Europe, Nat. Geog. Mag., Vol. 15, 1904, pp. 43–47.

M. Holtenberger. On a Genetic System of Sand Dunes, Bull. Amer. Geog. Soc., Vol. 45, 1913, pp. 513–515.

E. Huntington. The Pulse of Asia, Boston, 1907.

C. R. Keyes. Eolian Origin of the Loess, Amer. Journ. Sci., Vol. 156, 1898, pp. 299–304; Rock Floors of Intermont Plains of the Arid Region, Bull. Geol. Soc. Amer., Vol. 19, 1908, pp. 63–92; Deflation and the Relative Inefficiencies of Erosional Processes under Conditions of Aridity, *ibid.*, Vol. 21, 1910, pp. 565–598.

D. T. McDougal. Desert Basins of the Colorado Delta, Bull. Amer. Geog. Soc., Vol. 39, 1907, pp. 705–729; North American Deserts, Geog. Journ., Vol. 39, 1912, pp. 105–120.

P. Olsson-Seffer. Relation of Wind to Topography of Coastal Drift Sands, Journ. Geol., Vol. 16, 1908, pp. 549–564.

S. Passarge. Die Kalahari, Versuch einer Physisch-geologischen Darstellung der Sandfelder des Südafrikanischen Beckens, Berlin, 1904, 822 pp.

Raphael Pumpelly. Relations of Secular Rock Disintegration to Loess, Glacial Drift, and Rock Basins, Amer. Journ. Sci., Vol. 17, 1879, pp. 133–144; Smithsonian Contributions to Knowledge, Vol. 15, 1867, pp. 1–143.

Raphael Pumpelly, W. M. Davis, and E. Huntington. Explorations in Turkestan, Carnegie Instn. Publ. 26, Washington, 1905, pp. 1–317.

F. von Richthofen. On the Mode of Origin of the Loess, Geol. Mag., new series, Decade II, Vol. 9, 1882, pp. 293–305; China, Ergebnisse Eigener Reisen und darauf Gegrundeten Studien, 4 vols., Berlin, 1883.

I. C. Russell. Subaerial Deposits of the Arid Regions of North America, Geol. Mag., Decade III, Vol. 6, 1889, pp. 242–250, 289–295.

N. S. Shaler. Phenomena of Beach and Dune Sands, Bull. Geol. Soc. Amer., Vol. 5, 1894, pp. 207–212.

B. Shimek. A Theory of the Loess, Proc. Iowa Acad. Sci., Vol. 3, 1896, pp. 82–89; Papers on the Loess, Bull. Lab. Nat. Hist., Iowa State Univ., No. 5, 1904, pp. 298–381.

G. H. Stone. Wind Action in Maine, Amer. Journ. Sci., 3d series, Vol. 31, 1886, pp. 133–138.

R. S. Tarr and Lawrence Martin. Glacial Deposits of the Continental Type in Alaska (including loess), Journ. Geol., Vol. 21, 1913, pp. 295–300.

W. G. Tight. Bolson Plains of the Southwest, Amer. Geol., Vol. 36, 1905, pp. 271–284.

J. A. Udden. Erosion, Transportation, and Sedimentation Performed by the Atmosphere, Journ. Geol., Vol. 2, 1894, pp. 318–331; Dust and Sand Storms in the West, Pop. Sci. Monthly, Vol. 49, 1896, pp. 655–664; Loess as a Land Deposit, Bull. Geol. Soc. Amer., Vol. 9, 1898, pp. 6–9.

J. Walther. Das Gesetz der Wüstenbildung, Berlin, 1900, 1912; Die Denudation in der Wüste und ihre Geologische Bedeutung, Abhandl. Math.-phys. Classe Gesell. Wiss., Leipzig, Vol. 16, 1891, pp. 448–453.

B. Willis. Research in China, Vol. 1, Carnegie Instn., Publ. 54, 1907, pp. 183–196, 242–254.

J. B. Woodworth. Post-Glacial Eolian Action in Southern New England, Amer. Journ. Sci., 3d series, Vol. 47, 1894, pp. 63–71.

G. F. Wright. Origin and Distribution of the Loess in Northern China and Central Asia, Bull. Geol. Soc. Amer., Vol. 13, 1901, pp. 127–138.

V. Zeigler. Factors Influencing the Rounding of Sand Grains, Journ. Geol., Vol. 19, 1911, pp. 645–654.

TOPOGRAPHIC MAPS

In this and succeeding chapters all map references are to the standard quadrangles of the U. S. Geological Survey, unless otherwise specified. Other American maps will occasionally be referred to. No attempt will be made to cite the European and other foreign maps showing physiographic features, modern lists of which will be found, among other places, at the ends of the chapters in de Martonne's *Traité de Géographie Physique*, 1909; in Davis and Braun's *Grundzüge der Physiogeographie*, 1911; in Davis's *Erklärende Beschreibung der Landformen*, 1912; in Davis's discussion of *Large Scale Maps as Geographical Illustrations* (*Journ. Geol.*, Vol. 4, 1896, pp. 484–513); and in Martin, Bean, and Williams's *Laboratory Manual of College Geography*, 1913.

Gannett has published an excellent list of 100 American topographic maps, classified as to physiographic features shown, — *Topographic Maps of the United States showing Physiographic Types*, U. S. Geol. Survey, 1907. Other good selections may be found in Davis, King, and Collie's *Governmental Maps for Use in Schools*, New York, 1894; in Gannett's Folios 1 and 2 and Hill's Folio 3 of the *Topographic Atlas of the United States*, U. S. Geol. Survey, 1900; in the folios of the *Geologic Atlas of the United States;* in Jefferson's *Exercises on Topographic Maps*, 1906; in Salisbury and Atwood's *The Interpretation of Topographic Maps*, Prof. Paper 60, U. S. Geol. Survey, 1908; in Davis's *Practical Exercises*, 1908; in Emerson's *Manual of Physical Geography*, 1909; in Salisbury and Trowbridge's 3 laboratory manuals, 1912, 1913; in the author's *Laboratory Manual of Physical Geography*, New York, 1910 and 1913; and in several other American text-books and laboratory manuals of physical geography.

Wind Erosion and Deserts

Laramie, Wyo.	Toole Valley, Utah	Ballarat, Cal.
Granite Range, Nev.	Saypo, Mont.	Coldwater, Kan.

Sand Dunes

Moses Lake, Wash.	Holtville, Cal.	Yuma, Ariz.
Monterey, Cal.	Cherry Ridge, Mont.	Sandy Hook, N.J.
Easthampton, N.Y.	Syracuse, Kan.	Wyndmere, N.D.

Many U. S. Coast and Geodetic Survey maps, as Charts 119, 121, and 212, also show dunes. For maps showing the loess, see the atlas of *Geographical and Geological Maps* accompanying Willis's *Research in China*, 1906.

CHAPTER IV

THE WORK OF UNDERGROUND WATER

Entrance and Movement of Underground Water

Proportions of Run-off, Evaporation, and Percolation. — When rain falls upon the land, a part quickly runs off at the surface, a part is returned to the air by evaporation, and a part sinks or *percolates* into the ground. The latter is called *underground* or *ground water.* The proportion that pursues this latter course varies greatly, according to the rate and amount of the rainfall, the porosity of the ground, the dryness of the ground and air, the steepness of the slope, and the luxuriance of the vegetation which retards the run-off. It is, however, a very large percentage of the annual rainfall of most regions. Naturally less soaks into the ground where there are steep slopes for rapid run-off than from gentle slopes, on which the rain-water tends to stand; less where vegetation interferes with run-off than where it is sparse or absent; less into dense than into porous rocks; less into dry rock than into that already wet; and less where the rain is so heavy that it quickly forms tiny streams and rills than when the rain falls more slowly, and, therefore, runs off less readily.

The Movement of Water Underground. — That portion of the rain-water that enters the soil and rock passes along the cavities, both large and small, and enters upon an underground journey of greater or less extent, according to circumstances. A very considerable portion has a short journey, for much of it is evaporated either directly into the atmosphere or into the air that occupies the cavities when water does not fill them. The rise of such vapour by upward diffusion from the ground is a familiar fact to campers who have slept upon the ground and, in the morning, found their rubber blankets dripping with moisture. At all times such vapour is rising from the damp ground, and it is ascending even when the surface layer is quite dry.

Use of Underground Water by Plants. — Other portions of the underground water rise by capillary action, and still other portions are taken from the ground by the plant roots, and stored in the plant tissue, or given back to the air by evaporation from the leaves. This action of plants makes a heavy drain upon the moisture of the soil. It is in large measure the effort to obtain the necessary moisture that causes plants to send their roots over such large areas and to such depths. In arid climates the roots of a plant are often much more extensive than the part of the plant above ground; and in thin soils in humid lands the roots of trees often extend far from the tree, and the size to which the tree can grow is not uncommonly limited by the amount of moisture available within the reach of the widely spreading roots. Drain pipes are often split open and quite filled by a multitude of roots of a tree seeking this source of moisture.

Water Absorbed by Rocks. — Still another termination of the underground journey of water is in chemical combination with the rock-forming minerals, by hydration, during the process of weathering. While much water is thus locked up in solid form, it is undoubtedly far less than the proportion whose journey is quickly ended by evaporation and by the intervention of plants.

Water Long Detained Underground. — Other portions of the ground water enter upon much longer journeys, slowly seeping through the soil, subsoil, and even the solid rock, remaining underground for days, months, and even years, before reappearing at the surface, perhaps at a point far distant from the place of its entrance. Some may remain in the rocks for indefinite periods, and there is undoubtedly underground water in the crust of the earth that was locked up there in early geological ages. Such water may not return to the surface until brought up in hot springs, or during volcanic eruptions, or when, by denudation, it is brought near the land surface.

Source of Mine Water. — The presence of percolating water, even far below the surface, is often demonstrated by mines and other deep excavations, into which water seeps from the enclosing rock. It is one of the important and expensive tasks of mining to remove the water that enters from the surrounding rock, and if pumping is suspended for a time the water gathers in pools in the lower workings. Not all mines are wet, however, which proves that water is not percolating through all rock layers.

Porous Beds are Underground Reservoirs. — It is the more porous beds that offer the easiest path for underground water to follow, sometimes the porosity between the rock grains, sometimes the openings resulting from the mechanical breaks or joint planes that traverse the rocks. Some such porous beds, notably sandstones, are reservoirs of underground water, from which extensive supplies may be obtained by boring to them, and tapping the slowly moving supply which entered the bed, perhaps scores of miles away at some point where it outcrops at the surface. So slow is the percolation, even through such porous beds, that the water rising in a well fifty miles from the point of entrance may have required fifty or a hundred years to make the journey.

The Water Table

Depth of Permanent Saturation. — The zone below which the soil or rock is saturated is known as the water level or the *water table*

(Fig. 44). The depth of this varies greatly from place to place, primarily according to the climate and the porosity. In humid climates it may lie at the very surface, as in swamps, while in arid regions it may be hundreds of feet beneath the surface. The water table is also subject to change even in a given locality, rising during periods of rain and sinking during periods of drought, when it is lowered by the downward passage of water, by capillary rising, by evaporation, and by plant action.

Relations to Topography and to Gravity. — The surface of the water table is by no means level. Speaking generally, it roughly follows the contour of the land, though it is also influenced by porosity, and sinks to a lower level in porous than in more impervious rocks. It is, however, farther beneath the surface on hilltops than in valley bottoms, and this difference in depth becomes even greater in periods of drought than in rainy periods. Indeed, if there could be rainfall

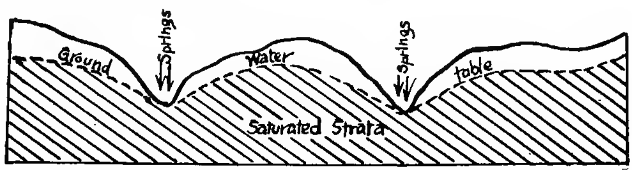


Fig. 44. — Relation of the water table to topography. (After Veatch.)

enough, the water table would coincide with the surface, and would, therefore, follow the topography exactly. That it does not do so normally is due to the fact that the water escapes faster than it is supplied, and this escape, while in part due to the causes stated above, is mainly the result of subterranean percolation. Underground, as well as at the surface, water tends to drain from high to low ground under the pull of gravity. In surface water this tendency finds immediate expression by the run-off; but underground water is checked in its motion by the cavity walls, and it can obey the pull of gravity only by slow percolation. Thus it is that the water table surface on a hill is well above the water table level in a contiguous valley; but, since the underground water is slowly obeying gravity by percolation, the water table of the hill sinks as the water percolates toward the valley. Consequently the water table is farther beneath the surface on the hill than in the valley, and in times of drought the level sinks still farther. The water table in the valley is in part supplied and kept near the surface by the percolation of underground water from the neighbouring higher ground, and the surplus is turned over to the stream to swell its volume. Thus the supply of underground water is an important factor in keeping streams fed and in conserving the rain-water and turning it over to the streams during periods between rains.

Wells

Relation to Water Table. — The presence of underground water is of great value to millions of persons as a source of water supply, especially those living in the country. By digging down below the water table a supply of water is insured, for the water seeps into the cavity from the water-charged subsoil or rock, rising in the well to the water table. As the water table rises and falls with the variation in rainfall conditions, the surface of the well slowly responds, lagging behind a little because of the time taken for the water to seep through the ground. In periods of drought the water table may sink many feet and shallow wells go dry, especially upon the higher ground; and at times of unusual dryness the water may go out of even deeper wells, and over wide areas a water famine may result. Such a condition cannot take place in a uniformly damp climate, but in the variable climate of eastern and central United States it occasionally occurs.

Depth of Wells. — The depth to which wells must be dug varies with the climate, being very shallow in humid regions, while in arid climates dug wells are quite impossible away from water courses. It also varies with the topography, it being necessary, in general, to dig deeper wells on hilltops and upper hillsides than in valley bottoms and on lower hill slopes, because of the position of the water table described above. There is also a variation dependent upon porosity, as might be expected. At times, too, there are underground zones of more rapid percolation, as along joint planes, or along bedding planes, especially where a porous bed rests upon a more impervious one. Such positions are peculiarly favourable to large and steady supply; but even such supplies may be subject to exhaustion when the water table is lowered by drought. There is no known way of determining the existence of such underground water bodies without actual digging, notwithstanding the claims of the so-called " water witch " to be able to do so, the reported success being doubtless due to the fact that there is a water table, and that a well dug below it is certain to have water.

Pollution of Wells. — Since the water supply of dug wells is rain-water that has entered the ground, upon an underground journey in which it has been interrupted, perhaps but a few score yards from the point of entrance into the ground, well water is subject to danger of pollution, which is further increased by the danger of surface wash finding its way into the well. Carelessness or ignorance in location of wells in relation to barns and other sources of possible pollution has been, and still is, the basis for a large amount of disease in country districts. Even though partially filtered through a few yards of soil, barnyard drainage is never a healthful beverage. Even a well uphill from the barnyard may be polluted if a porous layer, sloping downward from the barn, goes beneath the well.

Springs

Nature of Springs. — In certain situations underground water outflows at the surface, seeping out in small quantities, or in places flowing out with considerable volume. Where the outflow of underground water is somewhat concentrated it is called a *spring*. This concentration may be brought about by a variety of causes; and, according to the degree of concentration, the spring may be either of small or of large volume; or it may be temporary or permanent, according as the supply is variable or constant.

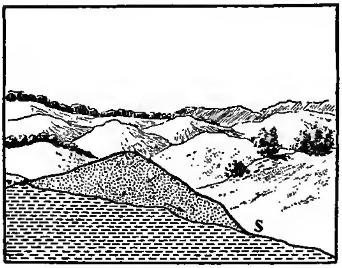


Fig. 45.—Emergence of a spring at S, where porous glacial deposits overlie impervious rock on the side of a valley.

Causes of Springs. — Springs are common on hill slopes and in valleys because the valley table is being lowered by the passage of underground water from higher to lower levels. A multitude of springs and less concentrated seepage supply streams with water as a result of this movement and outflow. During and immediately after wet spells many springs develop, which run dry during periods of drought. In the spring, when the water table is normally high, there are numerous, wet, boggy places on hill slopes which may quite dry up during the drier period of summer; but there are many springs whose supply is constantly maintained, coming, as it does, from deeper sources. Such springs are commonly cold, even in the midst of summer, for their water comes from deep enough to be beyond the influence of the annual temperature change.

Among the causes for so concentrating water as to lead to the development of springs, one of the most common is variation in porosity of layers. When, for example, water falls upon a porous layer beneath which is a more impervious one, it tends to flow along the junction of the two layers, provided either that the slope of the junction is downward or the pressure of the water table gives a sufficient head to force it along. If this junction of the two layers extends to the surface at a lower level than the entrance of the water, it will flow out at that point, very often as a spring or a series of springs. The junction of glacial drift with rock on a valley side is often the site of springs (Fig. 45).

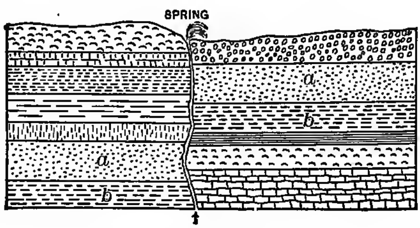


Fig. 46.—A spring determined in position by a fault plane.

Joint planes and bedding planes in rocks frequently serve as the guiding paths of sufficient quantities of underground water to give rise to springs. Fault planes extending deep into the earth (Fig. 46) are paths along which underground water passes, rising to the surface when under sufficient head. The sites of faults are not uncommonly marked by the issue of copious springs, arranged in a line along the fault plane. Still another cause for springs is the issue of underground streams in limestone countries. Such springs are often of large volume, being veritable streams even at the point of issue.

Artesian Wells

Necessity of Deep Wells. — Springs can occur only where a zone of ready percolation extends to the surface; but there are many such zones underground which do not rise to the surface. If, however, these are reached by a boring, the water will rise in the boring, and, if the pressure is sufficient, will flow out at the surface, or even rise like a fountain fifty feet or more in the air. Such a boring in which water rises is called an *artesian well*. By some usage an artesian well is one in which the water actually flows out at the surface, and this was the original meaning of the term; but since there are all gradations from those that outflow to those in which the water rises only part way to the surface, the term artesian well is coming to be used for any bored well in which the water rises from an underground source. Where it does not actually outflow it is commonly pumped to the surface by windmills or gasoline engines.

Artesian Water in Synclines. — The name artesian comes from the province of *Artois* in France, where such wells have long been known, but artesian wells are now widely distributed. In *Artois* the wells occur in a valley, beneath which the strata extend, while rising on the valley sides. Such a system of downfolded strata is called a *syncline*. The water, entering the rock layers on those enclosing hills, sinks down into them, passing most easily along a porous layer and being prevented from rising in the valley bottom by an overlying bed of more impervious rock, I. The porous layer is, therefore, filled with water under considerable pressure. When tapped by a boring, the pressure drives the water up and causes it to outflow (Fig. 47); but the water of the artesian well does not rise quite as high as the head which supplies the pressure, because the effect of the pressure is partly lost by friction in passage through the rock pores and crevices.

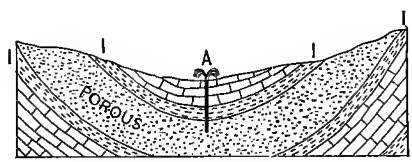


Fig. 47. — Artesian well at A in a syncline.

Artesian Water in Monoclines. — Such an arrangement of rock layers as that described above is of course neither common nor widespread; but it has been found that even a single inclination of rock layers, a *monocline*, will give rise to conditions favouring artesian wells, and this is far more common. The necessary conditions are (*a*) a porous rock layer, outcropping in a region of rainfall, and dipping into the earth (Fig. 48), (*b*) an overlying bed sufficiently impervious to prevent the ready escape of the water in the porous bed, (*c*) no ready downward escape for the water, which means either saturated or impervious rock below. In such a set of conditions the water slowly percolates along the porous bed under the pressure of the column of water which fills the bed. If tapped by a well at a point lower than the point of entrance of the water, an artesian well will be formed in which the water rises to the height which the pressure determines.

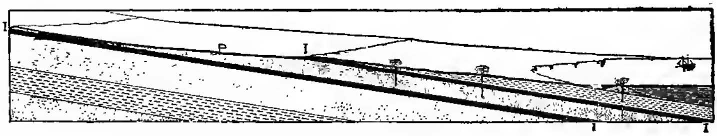


FIG. 48. — Artesian wells in a monocline and on a sand bar.

Artesian Wells of United States. — Artesian wells are found in many parts of the United States. Some of them are very shallow wells in the deposits of glacial drift, obtaining their water from depths of from fifty to two or three hundred feet, from layers of sand. Such wells are usually of small volume, their water source is local, and if many wells are bored to it the water may be exhausted. Other wells go into the bed rock to depths commonly of from 50 to 1000 feet, and in some instances to depths of 4000 feet.

There are certain regions where the conditions are favourable to the development of artesian wells over wide areas, where an extensive sheet of porous rock dips gently beneath the surface, receiving a large supply of water from a broad outcrop area. One of the most extensive areas is along the plains which skirt the Atlantic and Gulf coast south of New York, where there are great numbers of artesian wells. Some of these wells, as at Atlantic City (Fig. 48), go far below the sea level and bring up fresh water from the deep lying porous bed. There is another extensive artesian area in the Upper Mississippi valley, and another in the Great Plains of South Dakota, Nebraska, and Kansas, where the water supply enters a porous sandstone that outcrops farther west.

Uses of Artesian Water. — Artesian wells, from some of which the water must be pumped, are an important source of water supply for municipal purposes, mainly for small towns and cities, though furnishing a partial supply for even large cities. Such wells are also used for factories and for homes; and in the arid western United States some use is made of artesian water in irrigation. Even in the best artesian well areas there is a limit to the available supply, and therefore too many wells within a restricted area may lead to partial exhaustion of all. The water, though often charged with mineral matter in solution, is pure and usually excellent for drinking purposes; but the limited supply makes it impossible to utilize this source of pure water in large cities.

Mineral Springs

The Mineral Load of Water. — In the study of weathering it was pointed out that water percolating into the earth performs chemical work of solution and alteration of the rocks. It follows, therefore, that where such water rises to the surface again it will bring with it some of these soluble materials. As a matter of fact, all water escaping from under ground is more or less charged with mineral matter in solution, although it entered the ground as pure rain-water. In the majority of cases the mineral in solution is in such small quantities that it would ordinarily escape detection; but very often it produces such noticeable results that the fact of the presence of mineral has led to the common term of *mineral springs*. There are a multitude of different substances known in such springs, but here only a very few will be mentioned.

Hard Water. — The " hardness " of water, so well known in contrast to the " softness " of rain-water, is the result of the presence of carbonate of lime or magnesian carbonate of lime, or gypsum, or other mineral salts in solution in sufficient quantities to decompose soap and form insoluble compounds with its fatty acids, which settle as a whitish precipitate. Where carbonate of lime is even more abundant, it may be precipitated around the spring, forming a calcareous deposit, this precipitation often being induced or aided by the growth of plants. Very extensive deposits of *calcareous tufa* are sometimes made around springs in limestone regions. Other springs bring to the air so much iron in solution that iron deposits are made around them.

Medicinal Waters. — Some springs are sour and acid; some alkaline; there are sulphurous springs, brine springs, and springs charged with carbon dioxide, like a natural soda water; and some of the springs are hot, others cold, even some down nearly to the freezing point. Many of these spring waters have medicinal properties, and hotels, sanitariums, and baths for invalids and others who seek their beneficial properties are built where they outflow; while the waters of others, like Vichy and Apollinaris, are bottled and sent to all parts of the world. Many of the best-known medicinal and mineral spring waters are found either in regions of recent volcanic activity or in regions of faulting, which gives opportunity for deep-seated waters to rise to the surface.

Hot Springs

Cause of Hot Springs. — Although the water of most springs is cool, having the temperature of the ground below the influence of annual temperature change, there are many that are warm or hot, and some in which the temperature is at the boiling point. Such springs are most common in volcanic regions, and the source of heat is, with little doubt, to be ascribed to volcanic sources. Even in regions where the volcanic activity has died out, intruded lava doubtless still exists beneath the surface, and, thus blanketed by overlying rock, it may require thousands of years before such heated rock will completely cool. Other possible sources of heat are (*a*) chemical change, (*b*) friction, as rocks are moved and ground against one another, (*c*) heat possibly inherent deep below the surface, and (*d*) radio-activity.

In individual cases it is not usually possible to determine the exact source of the heat, and it becomes especially difficult in regions remote from recent volcanic activity. However, in such cases, the heated waters usually arise along fault planes, which may lead deep down into the earth and thus give opportunity for water to arise from the depths. Among medicinal hot springs are those of Carlsbad, Saratoga, and Hot Springs, Ark., the latter said to be salutary because of their radio-activity, although this last has been questioned.

Hot Spring Deposits. — Heated water has a higher solvent power than cold water, and there are usually gases and solutions in such water that greatly aid it in its power of altering and dissolving mineral substances. Accordingly, the water of hot springs often brings a large quantity of dissolved mineral matter to the surface, and deposits about such springs are often extensive. This is illustrated around the hot springs of New Zealand and the Yellowstone National Park, where successive terraces are built up around the hot springs, forming extensive deposits of carbonate of lime or calcareous tufa (Fig. 49). Here a part of the colour for which these terraces are famous is due to the presence of minute plants, or *algæ*, which grow in the hot water, and aid in the deposit of the mineral. The amount of dissolved mineral matter may be inferred from the fact that the Excelsior cauldron in Yellowstone Park pours out 4400 gallons of boiling water per minute.

Formation of Veins. — In hot spring waters are a great variety of mineral substances, even including salts of metallic substances. It is quite certain that mineral veins are even now being deposited by these hot waters along the cracks through which they are rising to the surface. Certainly in the past, the ascent of heated waters along fault planes and other zones of percolation has been responsible for the deposit of mineral veins at present being worked as a source of precious and other metals. As the water rises and cools, or as it loses some of its gases, or as solutions of various kinds are mingled, or by chemical change in the minerals of the enclosing rock, or for other reasons, some of the load of dissolved substances is deposited by the hot water in the passage through which it is rising, giving rise to *veins*. If among these deposits metallic salts are included, the deposit becomes a mineral vein. Not all mineral veins are of this origin, though many, including some of those of gold, silver, and copper, evidently are.

Relation of Ore Deposits to Mountains and Volcanoes. — Since crevices are needed for a free flow of heated underground water, mineral veins deposited by such water are most commonly found in mountain regions where the rocks have been subjected to such strains as to lead to breaking; and since heat is needed for the most efficient work of water in mineral vein formation, mineral veins are naturally most common in regions of former volcanic activity. It is in mountain regions, or regions of fracturing of the crust, that

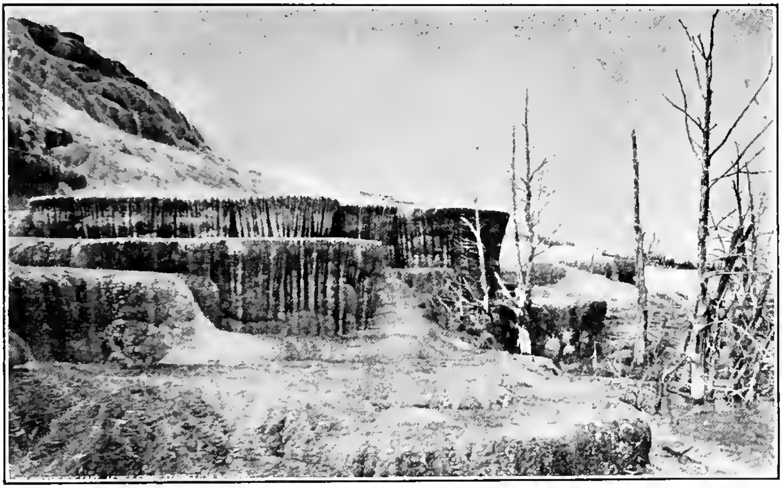


FIG. 49. — Terrace advancing over trees at Mammoth Hot Springs, Yellowstone Park. (Jackson, U. S. Geol. Survey.)

volcanoes develop, and, therefore, the two necessary conditions for the development of mineral veins occur commonly together. These facts have had local influence in determining the distribution of mining of the precious metals and others.

GEYSERS

Localities. — In a few localities, notably in Iceland, New Zealand, and the Yellowstone National Park (Fig. 50), certain hot springs have the habit of intermittent eruption, and are known as *geysers*. It is chiefly because of the large number and variety of these interesting phenomena in the last-named locality that an extensive tract of land has been set aside by Congress as a National Park, which is annually visited by thousands of people from all parts of the world, for this is with little doubt the most wonderful of all the geyser regions.

This is a region of former volcanic activity, and the outflow of heated water seems to be one of the dying phases of the vulcanism.

Geyser Basins. — In parts of the Park, notably within a few limited areas called "geyser basins," hot water issues from numerous vents, only a few of which, however, have the habit of intermittent eruption. Thus, while there are over 3000 known hot springs in the Yellowstone Park, there are only about 100 geysers. The hot springs vary greatly, some having but moderate flow and with temperature not very high, while others are at the boiling point, and some pour forth steady streams of hot water. In some of the hot springs steam bubbles rise from below, causing violent boiling at the surface, and even small explosions which, on a small scale, simulate geyser eruption.

Geyser Eruptions. — Among the geysers themselves there are also notable differences. In some the column of steam and heated water thrown up during the eruption is small, rises to a height of but a few feet, and the eruption is over in a very few minutes; while in others, a vast quantity of hot water and steam is expelled, during a period of an hour or more, and rising to a height of over 200 feet (Fig. 50); and between these extremes there is almost every gradation. In some the period of eruption is so regular that the time of its occurrence may be accurately predicted, while in others the eruptive period is irregular; and the interval between eruptions varies among different geysers from an hour or less to weeks and even months. Some of the geysers have erupted with regularity ever since the region was first discovered; others have become less regular, or have become extinct, while, on the other hand, some new geysers have come into existence.

Old Faithful. — Some of the best known of the Yellowstone Park geysers are the Old Faithful, Giant, Giantess, Castle, Beehive, Minute Man, and Lone Star, each erupting independently of the others and each with distinctive characteristics of its own. Among them one of the most remarkable is Old Faithful, which erupts with an interval of about an hour, sending a column of water and steam more than 100 feet into the air for a period of five or six minutes. Then it relapses into quiet for nearly an hour during which one may sit on the edge of its crater and look into the pool of heated water with perfect safety. At the end of the appropriate interval there comes another great rush of steam and water, thrown into the air with a roar. It sends out 3000 barrels of water with each eruption. For at least half a century this process has been repeated about 8000 times a year.

Geyser Deposits. — The heated geyser waters bear to the surface a variety of mineral substances in solution, among which the most important is silica, which is precipitated in a loose porous deposit called *silicious sinter*. This deposit is most extensive in the immediate neighbourhood of the orifice; and consequently around most of the geysers a cone has been built, on the crest of which is a depression, or crater, in which lies a pool of hot water and from which the eruptions occur. During and immediately after an eruption the surface of the cone is wet with the flood of hot water, and by each eruption a small addition is made to the cone. Similar deposits are being built around many of the hot springs.

Fig. 50. — An eruption of Old Faithful geyser in Yellowstone Park.

These silicious deposits usually have a varied form, due to irregularities of deposition and to the concretionary tendency, as a result of which spherical forms tend to grow as the silica is precipitated out of the hot water. There is also much beautiful colour, partly from the effect of light in the clear hot mineral water, partly from the influence of minute plants which live in the heated water and aid in the precipitation of the silica. When the supply of silica ceases, through the closing up of an orifice, the silicious sinter loses its colour, and crumbles under weathering to a chalky white powder. Here and there an extinct geyser cone is to be seen, offering a striking contrast to the highly-coloured cones of certain of the active geysers.

Cause of Eruptions. — While it is possible that more than one cause may operate to produce geyser eruptions, there is a single explanation that seems capable of explaining the phenomenon, and even of accounting for the different forms of eruption. This explanation assumes, first, that there is a fairly long, narrow, irregular orifice extending into the earth, that underground water finds its way into this orifice in fairly steady volume, and that it is heated in some part of its course. Under normal conditions this heated water will outflow as a hot spring, or, if the temperature is high enough, as a boiling spring. But among a multitude of such orifices some are so narrow and irregular, and the supply of heat is so great, that boiling is interfered with, and locally steam is generated down in the geyser tube, and the expansion of this steam lifts the column of water above and throws it into the air. This theory is supported by the fact that miniature geyser eruptions may be produced by applying heat to water in a long tube, imitating the assumed conditions in the natural geyser.

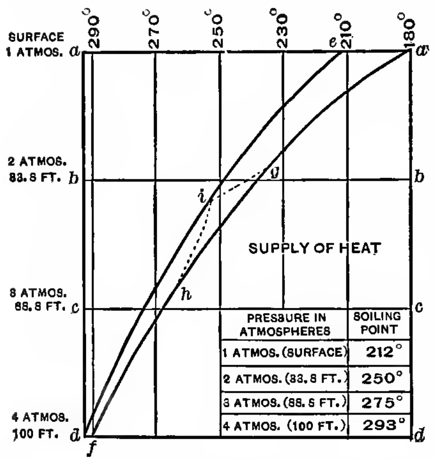


FIG. 51. — Diagram to show temperature and pressure conditions in a geyser.

The accompanying diagram (Fig. 51) is intended to illustrate the theory of geyser formation. The vertical lines represent temperatures, the horizontal lines depths in the earth. At sea level, with a pressure of one atmosphere, the boiling point of water is 212° F. Under two atmospheres the pressure at sea level with a column of water of 33.3 feet is 250°; under three atmospheres, or with a column of 66.6 feet of water, it is 275°; and under four atmospheres, with a column of water of 100 feet, the boiling point is 293°. Thus at a depth of 100 feet in a geyser tube, at sea level, a temperature of 293° is required to boil water.

The boiling point curve of water down to a depth of 100 feet is shown by the line *ed* in Fig. 51. The line *af* is intended to represent the actual temperature of water in a geyser tube after an eruption, and while the water is nowhere hot enough to boil at that depth, it is, nevertheless, well above the boiling point of water at the surface and throughout most of the depth. About midway down a supply of heat is assumed, which raises the temperature of the water through a given area *hig*, and actually reaches the boiling point at *i*.

In a broad, open tube, as soon as the boiling point is approached there will be convection, the heated water rising, and raising the temperature of the water column above; but in the geyser tube convection is interfered with by the narrowness and irregularity. Therefore, locally, steam is formed in the tube. This lifts the column of water above, and as the pressure is relieved the boiling point at that depth becomes lower than the water temperature and more steam forms, giving rise to a powerful force which is able to throw the water above into the air, accompanied and followed by steam. If a stone or sod is dropped into the geyser tube, or if the water is soaped, making it less liquid, an eruption is made to come more quickly than normal, because convection is still further interfered with.

This theory for geyser eruptions accords so well with the known facts, and so perfectly explains the phenomena, that it seems well established. It is not difficult to believe that differences in period of eruption and in mode of eruption among geysers may be due to variations in the form of the geyser tubes and to the amount and depth of the heat supply. It is a noteworthy fact that, although in each of the geyser basins there are a number of geysers, — often several are close together, — there is no evident sympathy between them. This fact indicates clearly that the phenomena of eruption are the outcome of conditions associated with the individual geyser.

That the geysers are associated in groups, or basins, indicates a certain relationship as to cause, however. Throughout each basin, for example, there is probably the same general source of water and of heat. This we naturally assume to be the still uncooled, intruded lava, since geysers are found in regions of recent or present volcanic activity. One of the most peculiar facts is the limited number of geyser areas in the world and yet the presence of about a hundred in a single region. This may be due to some peculiarly favourable condition of heat supply, or it may be the result of some peculiar condition giving rise to the form of tube necessary for geyser eruption. The latter seems the more probable, and there is some reason for believing that the development of the geyser tube is a result of deposit of mineral matter under favourable conditions. As silica is deposited on the walls of the tube a hot spring may be transformed to a geyser, and this, in turn, may ultimately become so clogged that eruption ceases, and even the outflow of water is cut off, leading to the extinction of the geyser.

The Formation of Caverns

Solution Underground. — All underground water is engaged in the solution of mineral matter as it percolates through the soil, subsoil, or rock; but the amount of solution varies greatly, according to the minerals which it encounters. In an extreme case, such as salt, the mineral is so readily dissolved that a common way of obtaining salt from layers deep below the surface is to let fresh water down to the salt, where it becomes a brine which is pumped to the surface and evaporated to procure the dissolved salt. Percolating water also dissolves salt from such layers, and this is a cause for salt springs, like those at Syracuse, N.Y., which early gave rise to a great salt-producing industry there. As the salt is dissolved, the surface of the ground settles irregularly, giving rise to local depressions in which ponds often develop.

Other rocks, more common than salt beds, are also subjected to extensive solution, notably of gypsum and limestone. The latter is the most widespread of readily soluble rocks, being in fact one of the most common rocks of the earth's crust; and the solution phenomena associated with the activity of underground water in limestone are, therefore, widespread. They produce notable results both underground and at the surface.

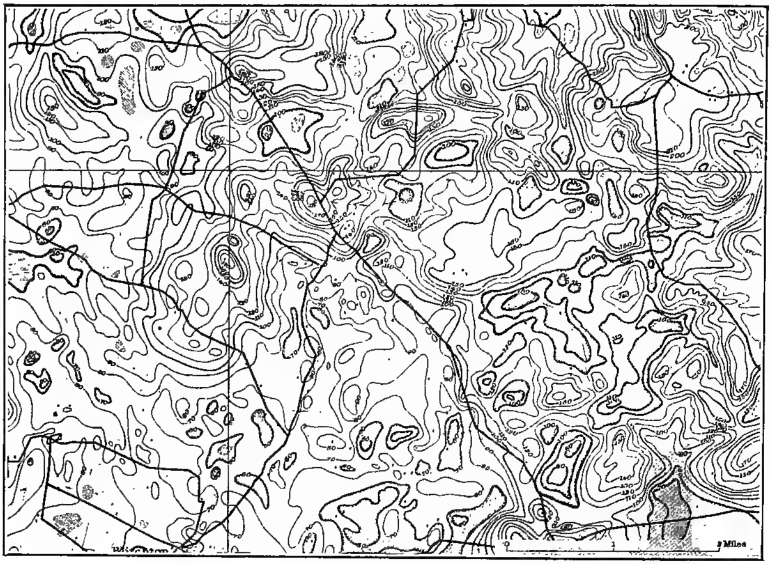


FIG. 52.—Map showing sink holes in Florida. (Williston Quadrangle, U. S. Geol. Survey.)

The Dissolving of Caves in Limestone. — In its entrance into limestone rocks water behaves as all percolating water does, following both the microscopic crevices and the larger cracks. Pure rain-water can accomplish little solution of limestone, but water containing carbon dioxide dissolves it with comparative ease. Consequently the crevices and cracks through which the water enters are enlarged by solution. As the process continues, a labyrinth of cavities is developed underground, often attaining such large size as to deserve the name cave or cavern, and extending for miles.

Sink Holes. — As a result of solution, the limestone is so honeycombed with cavities that water readily sinks into it, and during a rain the water disappears into the ground instead of running off in a multitude of rain-born rills. As the limestone is dissolved, the surface of the ground slowly settles, but it settles irregularly, and sometimes by the collapse of caverns. The topography, therefore, consists of a series of swells and hollows, the latter normally being roughly circular or elliptical basins. Toward these basins, called *sinks* (Fig. 52), the surface drainage flows, sinking beneath ground at the centre, which is sometimes an open cavity or pit, called a *sink hole*. At times, by the collapse of the walls, or by other means, these holes are closed, and then the surface drainage gathers in the basin to form a pond.

Underground Drainage. — The water that enters the sink holes, and that percolates into the cracks of the limestone, finds its way readily downward to a level that is determined either by the presence of an impervious layer, or by the influence of the surface rivers or other water to which the percolating water is tributary. From the cavern, drainage ultimately comes to the surface again, often as tributaries to large streams which flow even in a limestone country.

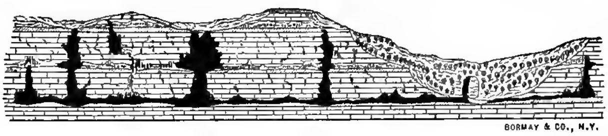


FIG. 53. — Relations of caverns at two levels to sink holes above, springs on a valley side, and a natural bridge. (After Shaler.)

These subterranean tributaries issue as springs in the river valleys and are often of large size. They are, on a much larger scale, analogous to the springs and seepage which contribute water to rivers in other regions, as underground water percolates from higher to lower water table areas. In limestone regions these springs are larger than in other regions, because the rock has been made more porous by solution and the underground water gathers in subterranean courses, which are at times of such size as to warrant the name underground rivers.

The level to which the underground tributary can work in cavern development is limited by the surface stream into which it flows, because its water must maintain a slope down to the surface stream. Consequently, the lowest part of the cavern is that nearest the surface stream, and its bottom will normally be nearly at the same level as the surface stream; and the cavern bottom becomes higher away from the outlet. If the surface stream is engaged in lowering its valley, the cavern outlet must either be lowered also, or be abandoned, for the water can then more freely pass into the limestone beneath the cavern, and, in time, so enlarge cavities as to drain the water at a lower level. Thus it happens in limestone regions traversed by gorges which are still being deepened, that a series of cavern outlets are seen on the gorge walls (Fig. 53), from only the lower of which a spring emerges, the upper ones being former outlets. And in caverns one often passes from one level to another, but only the lower levels are occupied by running water while the floors of the upper ones are often quite dry, because the water readily escapes to lower levels through crevices dissolved in the limestone.

The drainage of a limestone country is, therefore, of a peculiar type. There may be some streams of good size, as in other regions, but the tributaries are springs, rather than small surface streams, and most of the surface drainage finds its way into the ground, then, after a journey of greater or less length, emerges near the large streams, or lakes, or sea. In such a country one sees few surface streams; and these are chiefly large ones; and instead of a succession of linear valleys there is an undulating topography with numerous conical "knobs" and circular sinks. Such a *karst topography* is seen in southern Indiana and Kentucky in the United States, in southern France, in Austria along the eastern side of the Adriatic Sea, and in many other places. Here and there in limestone regions surface valleys abruptly terminate and the streams in these plunge into the ground, emerging at another point, often miles from the place of disappearance.

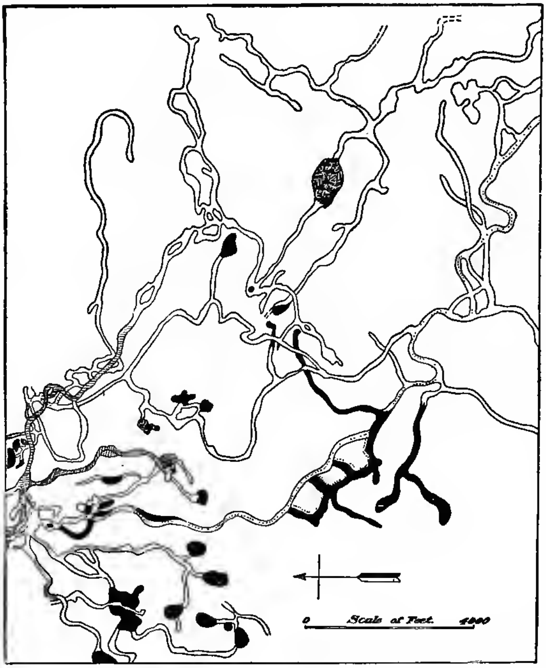


FIG. 54. — Map of part of the Mammoth Cave. (After H. C. Hovey.)

Cavern Systems. — The extent to which a system of caverns is excavated depends, in large part, upon the thickness of limestone and its extent. It is largely because of thick beds, lying in nearly horizontal position, that such an extensive labyrinth of caverns has been possible in Kentucky and southern Indiana, while in Virginia, where the limestone beds are thinner and tilted, the caverns are far more limited in extent. In Kentucky the limestone covers an area of about 8000 square miles, with an average depth of about 175 feet, and it has been estimated that there are at least 100,000 miles of cavern tunnels in it. One may travel on the surface, it is said, as much as 50 miles in certain directions without encountering running water, but there may be as many as 100 sink holes on a square mile of surface.

Mammoth Cave and Other Caverns. — It is in this limestone area that Mammoth Cave, the greatest in the world, is situated; but in the same country there are said to be 500 other caverns. The number of the tunnels and their extent are unknown, for they have never been fully explored, but there are certainly one or two hundred miles of connected galleries in the Mammoth Cave system (Fig. 54). These galleries are often winding; their height varies from a foot or two to over a hundred feet, and their width is similarly variable. There is often one gallery above another, and it is possible at points to go from one level to another. Here and there the cavern expands greatly, forming what is locally called a "dome," of which the highest is the Mammoth Dome, about 400 feet long, 150 feet wide, and from 80 to 250 feet high. It is so large that a good sized church, steeple and all, could be built in it.

Limited Value of Caverns. — Similar caverns are known in many regions; in fact, they are commonly associated with limestone strata in all parts of the earth. Among the thousands known, most are of small size, and are of little more than local interest; but some are widely known and much resorted to by visitors. Among those best known in the United States besides the Mammoth Cave of Kentucky are the Wyandotte Cave in Indiana, the Luray Cavern in Virginia, and Howe's Cave in New York. They have little direct value to man, though an attempt was once made to utilize the Mammoth Cave as a health resort for people with lung diseases, the idea being that the uniform temperature of the caverns (53°–56° F.) would be healthful; but the attempt was a failure. In the early history of the human race, caves served as the home of primitive man, and many of our best records of this early state have been recovered from cave deposits.

Cavern Deposits. — As a centre of scenic interest caverns attract large numbers of visitors and are, therefore, a resource of local importance. The interest is partly due to the marvellous labyrinth of natural underground chambers, and partly to the unique ornamentation of these chambers by deposits of carbonate of lime brought into them by percolating water. As the water oozes from crevices in the cave roof it bears in solution carbonate of lime, dissolved in its passage through the rock. By evaporation, oxidation, loss of gases, or change in pressure the water is forced to give up some of its dissolved load, and a pendant, icicle-like deposit slowly grows on the cave roof, forming a *stalactite* (Fig. 55). As the water drips to the cave floor a similar deposit, called a *stalagmite*, is built upward; and if the two deposits grow until they meet, a *column* is formed.

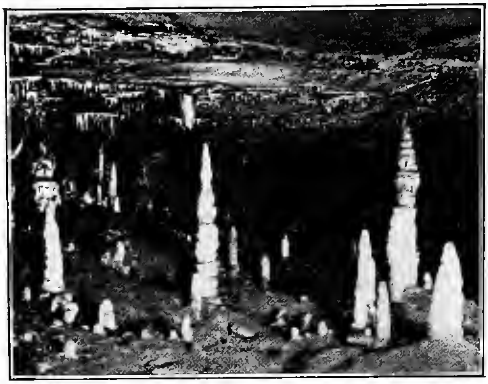


Fig. 55. — Stalactites, stalagmites, and columns in a Kentucky cavern.

These deposits are wonderfully varied in form as the water trickles over them and builds them up irregularly, giving rise to fantastic shapes. There is also variation in colour as the nature of the deposit varies, or some mineral impurity is introduced. Some of the caverns, like Luray, are marvellously beautiful in their ornamentation. The most highly ornamented caverns are those that have been formed longest, such as the upper galleries into which water has long been percolating from the roof.

Enlargement of Caves. — In the lower galleries of a cavern system the drainage often gathers such volume as to form a broad, deep stream underground, like the so-called river Styx of Mammoth Cave, on which boats may go. Doubtless in places the running water deepens the

Fig. 56. — Natural Bridge, Virginia. (Walcott, U. S. Geol. Survey.)

cavern by mechanical erosion, but most of the cavern excavation is the result of solution. There is a little coöperation of the atmospheric agents of weathering in enlarging the caverns; but in the still air and uniform temperature, and with the general absence of life in caverns, such action is of minor importance compared with solution. Now and then parts of the roof and wall are given such instability that

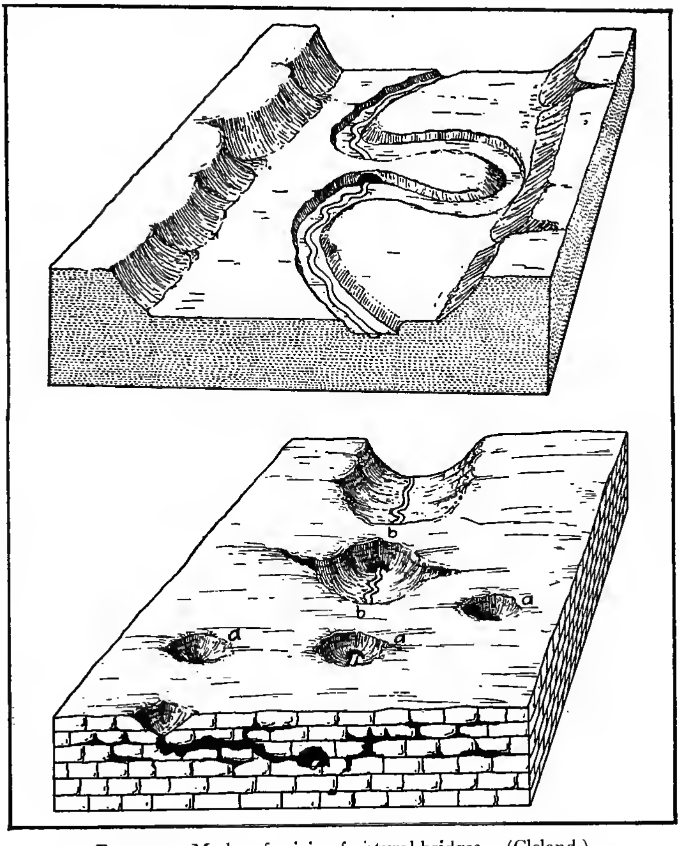


FIG. 57.—Modes of origin of natural bridges. (Cleland.)

they fall to the cavern floor, and during such falls earth tremors, or slight earthquake shocks, extend through the neighbouring region. Masses of rock that have so fallen may be seen here and there in caverns.

NATURAL BRIDGES

Natural Bridge of Virginia. — In limestone countries, arches across valleys, called *natural bridges*, are sometimes formed like the Natural

Bridge of Virginia (Fig. 56). The partial falling in of a cavern roof may leave such a natural arch, though few cases of this are known to exist. A more common cause for such arches is the disappearance of a surface stream into the joint planes of a limestone rock and its reappearance below. In time the water will excavate a valley beneath the arch, which then extends across the valley as a span or bridge. This is the origin of the Natural Bridge of Virginia, and of many other lesser examples.

Other Causes of Natural Bridges. — It has recently been shown that there are numerous other ways in which natural bridges may be formed, as by the outflow of lava from beneath a solidified crust, by irregular wave erosion on lake and sea coasts, and by stream erosion. The remarkable natural bridges of Utah, in sandstone, one of which has a span of 275 feet, and stands 308 feet above the valley bottom, is the largest known natural bridge in the world. It is due to the lateral swinging of a stream against a cliff from two sides, undercutting it until a hole has been cut through into which the river then passed, thus forming a natural bridge (Fig. 57).

Other Chemical and Mechanical Work of Underground Water

A Prime Factor in Weathering. — In the discussion of weathering, a phase of the work of underground water was considered in its relation to rock crumbling. This phase involved solution, decay, and the mechanical action of frost, and it was separated from the other phases of underground water work because it was a part of a complex process whose combined result was that of rock disintegration.

Deposition of Mineral Matter. — Much of the dissolved mineral matter derived by the underground water in its percolation is, as we have seen, brought to the surface and there either precipitated in deposits of mineral matter near the place of outflow, or contributed to the surface streams for transportation. But a part of the mineral load of percolating water is precipitated within the rock itself. Because of oxidation, or loss of gases, or chemical change, or other causes the water may be forced to give up some of its dissolved load, even though it has only just obtained it.

Cementation. — Such deposit naturally occurs most readily in the cavities of the rock, and this is the main reason why sediments are changed from the loose unconsolidated state to the condition of solid rock. The process is often to be seen in gravel banks where carbonate of lime or iron oxide has been deposited in sufficient quantities to cement the pebbles together. In Bermuda and in Florida loose coral and shell sand is quickly transformed to solid rock by deposit of carbonate of lime that the water has dissolved from some grains to deposit between others near by. It is by this process that sands are changed to sandstone, gravels to conglomerate, and shell and coral deposits to limestone. When buried deep in the earth and especially when subjected to the percolation of heated waters, rocks may become so firmly cemented that most of the pores are filled. Along larger cavities, such as joint planes and fault planes, veins of deposited mineral are found.

Replacement and Petrifaction. — The underground water enters even the very interior of rocks and causes many changes by solution and deposit. One form of such action is the replacement of one mineral substance by another, as, for example, the replacement of the carbonate of lime in a fossil by sulphide of iron, or by silica. This is called *petrifaction.* One phase of petrifaction is the replacement of the woody tissue of a tree or other plant by silica, when exposed to the percolation of silica-bearing water. This gives rise to *petrified wood,* in which, though the original structure is perfectly preserved, the material is no longer wood, but silica. In Arizona and other parts of western United States there are places where there are numerous entire tree trunks thus changed to stone, the so-called petrified forests.

Formation of Ore Deposits. — One of the most important results of the deposit of mineral substances by underground water is the formation of mineral veins. Some, as has been pointed out (p. 84), have been formed by the rise of heated water; but other deposits, notably iron, have apparently been made by descending waters, probably not heated. These have been formed by the removal of iron from soil and rock during the process of weathering and underground water percolation, and the concentrated deposit of some of the metal in favourable situations in the rock, or the removal of silica from a sedimentary rock made chiefly of iron and silica, leaving the iron as a very valuable ore deposit. This is thought to be the source of the great iron deposits of the Lake Superior region, upon which so much of the industrial development of the United States depends. Other mineral deposits are of similar origin.

Mechanical Work of Underground Water. — Underground water, except by freezing, is not a powerful mechanical agent. Yet the subject would not have received complete treatment, if it were not recognized that underground water, by dissolving here and there, or by giving rise to planes of slipping, is responsible for much slipping of rock and soil on slopes. Weathering and other phases of underground water work are responsible for the development of conditions of such instability that, under the pull of gravity, large and small masses move from higher to lower levels. While this process operates in a minute, invisible way, it also occasionally finds expression in a striking manner, when huge masses are abruptly dislodged and avalanched from steep slopes. Many landslides, and probably the great majority, are the result of the work of underground water, operating for long periods of time in preparation for the great final downfall, and, of course, coöperating with weathering and with gravity.

References to Literature

W. S. Blatchley. Indiana Caves and their Fauna, Indiana Dept. Geol. and Nat. Resources, 21st Ann. Rept. 1896, pp. 121–212.
F. Carney. Springs as a Geographic Influence in Humid Climates, Pop. Sci. Monthly, Vol. 72, 1908, pp. 503–511.
T. C. Chamberlin. The Requisite and Qualifying Conditions of Artesian Wells, 5th Ann. Rept. U. S. Geol. Survey, 1885, pp. 125–173.
H. F. Cleland. North American Natural Bridges, Bull. Geol. Soc. Amer., Vol. 21, 1910, pp. 313–338; Pop. Sci. Monthly, Vol. 78, 1911, pp. 415–427.
L. J. Cole. The Caverns and People of Northern Yucatan, Bull. Amer. Geog. Soc., Vol. 42, 1910, pp. 321–336.
B. Cummings. The Great Natural Bridges of Utah, Nat. Geog. Mag., Vol. 21, 1910, pp. 157–167.
N. H. Darton. Geology and Underground Water Resources of the Central Great Plains, Prof. Paper 32, U. S. Geol. Survey, 1905, pp. 190–372.
W. M. Davis. An Excursion in Bosnia, Hercegovina, and Dalmatia, Bull. Geog. Soc. Philadelphia, Vol. 3, 1901, pp. 21–50.
M. L. Fuller. Summary of the Controlling Factors of Artesian Flow, Bull. 319, U. S. Geol. Survey, 1908, pp. 1–44; Underground Waters of Eastern United States, Water Supply Paper 114, U. S. Geol. Survey, 1905, pp. 1–285.
J. C. Graham. Some Experiments with an Artificial Geyser, Amer. Journ. Sci., Vol. 145, 1903, pp. 54–60.
F. A. Grooch and J. E. Whitfield. Analysis of Water of the Yellowstone National Park, Bull. 47, U. S. Geol. Survey, 1888, 84 pp.
G. B. Hollister. A Curious Salt Pond in Kansas, Journ. Geog., Vol. 2, 1903, pp. 155–158.
W. H. Holmes and A. C. Peale. Yellowstone National Park, Geology, Thermal Springs, Topography, 12th Ann. Rept., U. S. Geol. and Geog. Survey of the Territories, Part 2, 1883, pp. 1–490, contains review of thermal springs and geysers of the world; **A. C. Peale**, Natural Mineral Waters of the United States, 14th Ann. Rept., U. S. Geol. Survey, Part 2, 1894, pp. 49–88.
H. C. Hovey. Celebrated American Caverns, Cincinnati, 1896; **H. C. Hovey and R. E. McCall**, The Mammoth Cave of Kentucky, Louisville, 1897.
T. A. Jaggar, Jr. Some Conditions Affecting Geyser Eruptions, Amer. Journ. Sci., Vol. 155, 1898, pp. 323–333.
F. H. King. Principles and Conditions of Movements of Ground Water, 19th Ann. Rept., U. S. Geol. Survey, Part 2, 1899, pp. 59–294.
W. von Knebel. Höhlenkunde, mit Berucksichtigung der Karstphänomene, Brunswick, 1906, 222 pp.
W J McGee. The Potable Waters of Eastern United States, 14th Ann. Rept., U. S. Geol. Survey, Part 2, 1894, pp. 1–47.
E. A. Martel. L'Evolution Souterraine, Paris, 1908, 388 pp.
Albrecht Penck. Über das Karstphänomen, Vorträge des Vereines zur Verbreitung Naturwissenschaftlicher Kenntnisse in Wien, XLIV Jahrgang, Heft 1, 1903, 38 pp.
N. S. Shaler. Aspects of the Earth, New York, 1889, pp. 98–142.
C. S. Slichter. Theoretical Investigations of Motion of Ground Water, 19th Ann. Rept., U. S. Geol. Survey, Part 2, 1899, pp. 295–384; Water Supply Paper 67, U. S. Geol. Survey, 1902, 106 pp.
J. E. Todd. Geology and Water Resources of a Portion of Southeastern South Dakota, Water Supply Paper 34, U. S. Geol. Survey, 1900, 34 pp.
C. D. Walcott. The Natural Bridge of Virginia, Nat. Geog. Mag., Vol. 5, 1893, pp. 59–67.
L. F. Ward. Petrified Forests of Arizona, Smithsonian Instn., Ann. Rept. for 1899, pp. 289–307.

W. H. Weed. Formation of Travertine and Siliceous Sinter by the Vegetation of Hot Springs, 9th Ann. Rept., U. S. Geol. Survey, 1889, pp. 613–676; Geysers, U. S. Dept. of the Interior, Washington, 1912, 32 pp.

TOPOGRAPHIC MAPS

Waterloo, Ill.	Princeton, Ky.	Weingarten, Mo.
Williston, Fla.	Citra, Fla.	Bloomington, Ind.
Pikeville Special, Tenn.	Williamsport, Md.	Natural Bridge Special, Va.
Administrative map of Yellowstone National Park.		Petrified Forest, Ariz.

CHAPTER V

RIVERS AND RIVER VALLEYS

General Considerations

Nature of Rivers. — A river is a natural drainage line on the land. It is the means of disposal of the surplus water which falls as rain or snow, and its movement depends upon the pull of gravity, by which the liquid water, in being drawn toward the earth's centre, seeks the point nearest the centre that is most accessible; that is, it flows down grade. Accordingly rivers will be found on any land surface where rain falls and where there is slope sufficient for it to run off.

Source of River Water. — The water supply of a river comes partly from the direct rainfall, from the surface run-off either of rain or melted snow or ice, and partly from water that has first entered the ground and after a period of activity as underground water has emerged at the surface again in springs or by seepage. By a multitude of contributions from these two sources the river is kept supplied regularly or irregularly according to conditions, and is large or small according to the length and the volume of water contributed. In general features, and in origin, no distinction can be drawn between the small stream and the great river; yet in individual characteristics there are vast differences among rivers.

Work of Rivers. — Incidental to the run-off of the surplus water there are some results of the highest importance. The land is drained, and accompanying this drainage is the transportation of a vast quantity of rock material, some *in solution*, some *in suspension*, and some *dragged* along the river bed. By the movement of the water, and largely by the use of the transported rock material as scouring tools, valleys are cut in the land, along the lowest part of which the water runs in a narrow channel, thus concentrating the energy of the running water. Finally the larger part of the rock material transported by the river ultimately finds a place of deposit. A river is, therefore, an agent of removal, not only of water, but of rock waste. Rivers are the most potent agencies for the sculpturing of the land surface and for the removal of the products of disintegration.

Rivers and Man. — The relation of rivers to the occupation of the land by man is intimate and fundamental in importance. They help to make the valleys open routes of travel, often into and even across mountain ranges, as well as upon less rugged land surfaces; or at times, the valleys are so deep and narrow as to interfere with travel.

River deposits make fertile, level land and are often the seat of a dense agricultural population. The river water is useful for navigation, for watering desert lands by irrigation, as a water supply for many purposes, as a source of water power, as the home of valuable food fish, and for other purposes. In these and other ways rivers are closely linked with the past history of mankind, and with its present life and pursuits. Among the phenomena of physical geography rivers rank as one of the most important, and a study of them leads us along a number of lines of inquiry, the first of which is the manner in which the river performs its tasks.

Rain Sculpturing

Run-off. — The simplest lesson in river work is that which can be learned from the examination of the process of run-off on a bare slope during a heavy rain, a process which can be experimentally imitated by turning a spray upon a surface of loose earth. If the surface be originally smooth, though with a slope, the water will at first form a sheet, some of which sinks into the earth, while a general movement starts down the slope. Quickly, however, the sheet will break up into a multitude of little rills as the current locally removes some of the loose earth, forming depressions toward which more and more water drains as they grow deeper. As erosion continues, the tiny rills become sunk in steep-sided valleys a few inches deep and a few inches wide, and from the steep sides the earth slides into the water, broadening the valleys.

Rill Work. — Here and there, where a pebble lies in the course of the rill, or where it crosses a layer a little harder than the rest, the current increases to a rapid, or the water tumbles in a small fall. One rill joins another, and the combined current of these two receives additions from other rills and steadily grows in size; and with increased volume the valley becomes broader and deeper. The water that has cut these valleys has thereby imposed upon itself the task of transporting the material thus removed, and it is consequently clouded with sediment. If, perchance, the water reaches a more gentle slope, or a small pool of standing water, its current is so checked that some or all of the sediment load is deposited.

Relation to River Work. — In miniature, this is an imitation in fundamentally important respects of river work in drainage, erosion, transportation, and deposition. Larger volumes of water, operating through long periods of time, but employing the same methods, have excavated similar valleys hundreds of miles in length, scores of miles in width, and thousands of feet in depth, even in the hardest rocks. Multitudes of such rivers, both large and small, have profoundly sculptured the surface of the lands, and removed from them thousands of feet of rock during the long ages of the geological past. And the rock waste which they have moved has been deposited in other places and has contributed the materials out of which new land has been made.

Bad Land Topography

Humid Bad Lands. — The action of rain wash in sculpturing loose earth in the manner described above may commonly be seen in ploughed fields, and during heavy rains such fields are deeply gullied (Fig. 58). In places the continuation of the process has greatly sculptured deposits of clayey nature, giving rise to topographic forms

Fig. 58. — Gully produced by headwater erosion in California. (Gilbert, U. S. Geol. Survey.)

called *bad lands*. Local areas of bad land topography are found in humid climates, as in the Austrian Tyrol near Botzen, in the clay cliffs of a portion of the southern shore of Lake Ontario west of Oswego, and in some of the abandoned plantation land of Louisiana.

Arid Bad Lands. — Typical bad lands, however, are characteristically phenomena of arid climates, and it is here only that they occupy extensive areas. There are many such bad land tracts in the arid western part of the United States, but they are especially well developed and extensive in western Nebraska, North and South Dakota, and Wyoming. Here there are scores of square miles in which rain sculpturing has so gullied the land that even travel across the surface is difficult because of the innumerable, deep, steep-sided gullies, and the narrow, intermediate ridges. Since no vegetation can grow upon the changing slopes, and since the topography is so irregular, such regions are shunned by man and even by most kinds of animal life (Fig. 59).

Earth Pillars. — In a bad land country sculpturing has often developed not only gullies and ridges, but isolated columns, often fantastically shaped. One of the common types of form is the column, capped by a boulder or by a slab of harder rock, and called an *earth pillar*. As the clay is removed by rain wash, boulders in the clay, or portions of harder layers, such as cemented sandstone, resist the

Fig. 59. — Bad lands in China produced through deforestation. (Willis.)

process and protect the underlying clay from removal. Thus ultimately a narrow column is left standing, bearing on its crest the cap of hard rock to which its presence is due. Frequently groups of such earth pillars are found close together.

Causes of Bad Lands. — For the development of bad land topography an easily removed rock, like unconsolidated clay, is necessary, and for the more perfect development an arid climate also. The aridity aids in the development apparently for four prime reasons: (1) the nature of the rainfall, which, though rare, commonly comes in the form of heavy showers, during which much work of rain sculpturing is possible; (2) the general sparseness or absence of vegetation, thus permitting rapid run-off and effective erosion; (3) the inefficiency of weathering, as a result of which the forms produced by rain wash tend to remain as formed; (4) the compactness of the soil in the warm, dry air, which tends to prevent removal during intervals between rains.

Sources of River Water

Relation to Precipitation. — The ultimate source of river water is the rainfall and snowfall. Murray estimates that the total annual rainfall on the land is over 29 million cubic miles of water. Of this a fourth or a fifth goes to the sea by the rivers. This comes to the river in unregulated run-off during and immediately after a rainfall, or during periods of snow or ice. Rivers also have a more or less perfectly regulated supply from underground water. The first of these sources is notably variable, while the second is normally far more uniform.

Floods and Low Water Stages. — The variability of the water supply of rivers is illustrated in all regions by the fluctuations in volume. After heavy rains or melting of snow, the run-off may become so great as to exceed the capacity of the river channel to hold it all, when the river rises in flood and overflows its banks and the country bordering them. In periods of drought, the supply may come wholly from underground, and the volume may sink so much in arid and desert lands that seepage and evaporation are able to dispose of it, leaving the stream bed quite dry. Among rivers there are great differences in respect to volume. Some receive a fairly steady supply, others are markedly irregular in volume (Fig. 60).

Underground Supply. — Among the factors tending toward regulation of river volume the most widespread is the supply of water from underground; but there are places, as in arid lands, where this source of supply is limited and even quite absent; and there are times, even in humid lands, when smaller streams dry up entirely during periods of drought. Indeed, all the rills and minor rivulets, which are flooded with water during rains, quickly dry up by run-off, seepage, and evaporation almost as soon as the rain ceases. In large rivers, however, with numerous tributaries draining thousands of square miles of country, there is almost certain to be a sufficient supply of water from underground to tide over any period during which no rain is falling in any part of the drainage basin. Thus the Mississippi, while it may rise in flood, can probably never so shrink in volume as even to approach dryness.

Supply from Lakes and Glaciers. — Lakes and swamps serve as regulators of river volume, storing water in times of flood, and supplying it in regulated volume both during rainy periods and droughts. To a lesser degree porous rocks, like beds of sand, likewise serve as storage reservoirs for water through seepage and consequently as river regulators. Mountain snows and glaciers lock up water which is contributed to rivers at times not related to the period of precipitation. In general this supply is fairly regulated, increasing in the warm months, and sometimes even giving rise to floods when snow melting and heavy rains occur at the same time. The melting of mountain snows, and rains among mountains, are important reasons why many

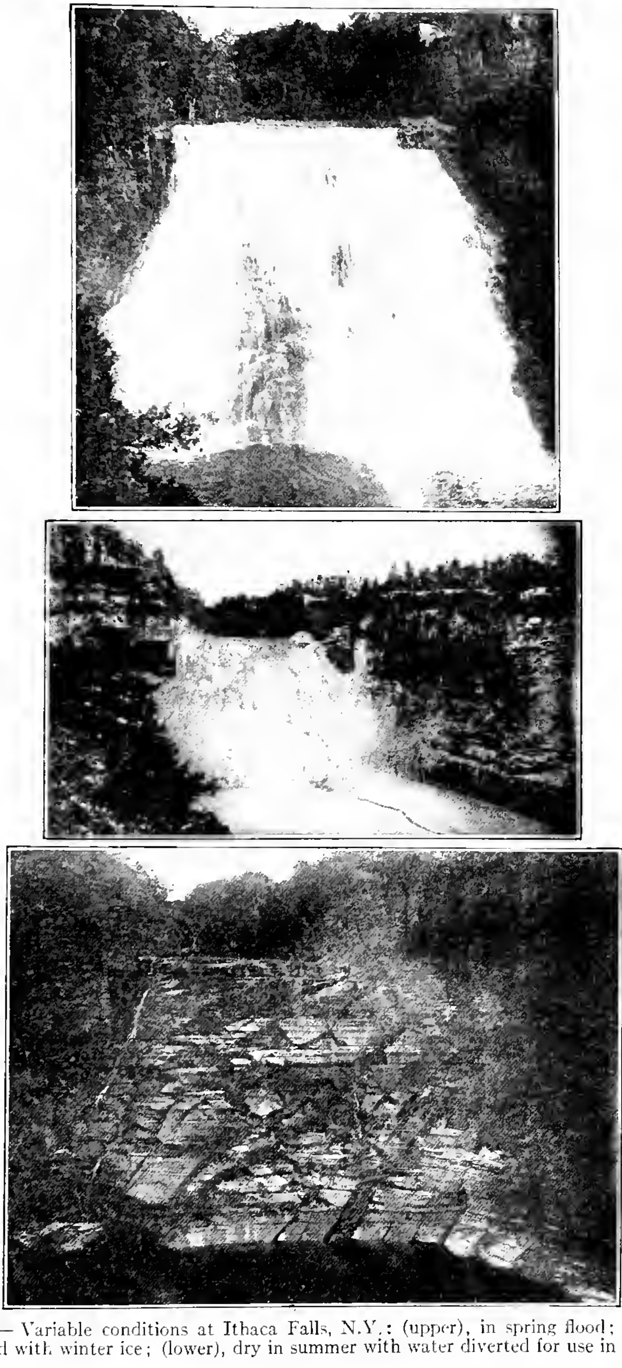


Fig. 60.— Variable conditions at Ithaca Falls, N.Y.: (upper), in spring flood; (middle), covered with winter ice; (lower), dry in summer with water diverted for use in a mill.

large rivers are kept supplied with water in their lower course during periods of drought. This is true, for example, of the Mississippi, many of whose tributaries rise among the Rocky Mountains, where they receive volume enough to carry them across the arid plains. It is true also of the Colorado River and the Nile, both of which are so well supplied with water that they are able to maintain a course across desert lands.

Relation to Run-off. — Variability in river volume may arise either from a great increase in amount of water available, or from favourable conditions of run-off. The former results either from heavy rainfall or from rapidly melting snow or ice. The latter is more complex; for the rate and amount of run-off depend (*a*) upon supply, (*b*) upon the slope, (*c*) upon rock porosity, and (*d*) upon obstacles to run-off. A moderate rainfall, upon a gentle slope, of fairly porous rock, and covered by a forest will give rise to only slight and slow run-off. A heavy rainfall upon a surface otherwise similar will result not only in a greater run-off, but in the run-off of a larger proportion of the rainfall.

Relation to Forests. — The forest is an important obstacle to rapid run-off, for the moss and undergrowth, and the litter of decaying vegetation, act like a sponge, absorbing large quantities of water; and they also introduce obstacles to the easy run-off of the surplus water. The removal of the forest is, therefore, an aid to ready run-off, and consequently tends toward greater variability in river volume. There seems little reason to doubt that the removal of the forest from parts of the United States has led to greater variability of river volume, and to increase both in size and frequency of floods.

Arid Land Variations. — The greatest variability in river volume is found in arid lands. There, during heavy rains, the water runs off readily from the barren slopes, and the streams rise quickly to torrential volume; but they subside almost as quickly, and soon the river bed is quite dry. Such streams are called *intermittent*, and they may be without water for months, or even for years in some desert lands.

Spring Floods. — Streams in frozen lands are also variable, for when it rains the water cannot sink into the frozen earth, and must all run off; and, added to it, is a supply from the melting of the frost in the ground. Thus even a light drizzling rain causes the streams to swell rapidly; but when the winter sets in they are frozen and cease to flow. Some of the winter and early spring floods of the United States are in large part due to the fact that the ground is still frozen so that none of the rain or melting snow water can enter it, thus giving rise to rapid and excessive run-off, during which one thing or another causes rivers to overflow their banks and inundate fields and towns. In regions of dense population these are particularly destructive, for example at Passaic and Paterson, N.J., in 1902, at Kansas City in 1903, at St. Louis, etc. The flood damage to railways alone in United States from 1900 to 1908 is estimated at $85,000,000, and this was probably only a tenth of the total damage to property through floods in these eight years.

The flood in Ohio in March, 1913, during which Dayton and over 200 other towns were inundated, resulted in the loss of over 400 lives

FIG. 61. — Flooded street in an Ohio town in March, 1913. (U. S. Geol. Survey.)

and damages to houses, bridges, railways, etc., amounting to over 190 million dollars (Fig. 61). It was caused by heavy rainfall, from 8 to 10 inches falling in parts of Ohio and Indiana in 5 days, supplying 560 billion cubic feet of water. There was no snow on the ground and it was not frozen, but it had been so saturated by heavy rains in January and the first part of March that practically the whole 8 to 10 inches had to be disposed of by run-off.

Floods are also sometimes due to the failure of dams, following heavy rainfall or melting of snow. This was the case at Johnstown, Pa., in 1889, when over 2000 people were drowned, and in Wisconsin in 1911, when a large part

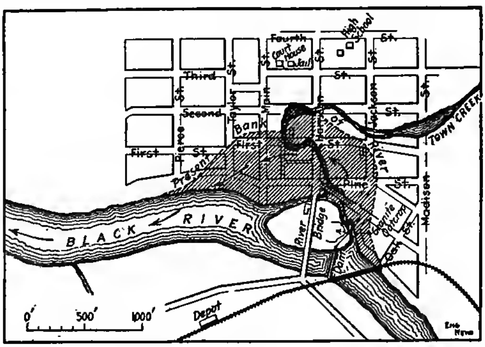


FIG. 62. — Sketch map of eroded area at Black River Falls, Wis. (After Pence.)

of the city of Black River Falls was destroyed by erosion of a river bluff during a flood (Figs. 62, 63). This last was not a spring flood, however, occurring after heavy rainfall in October.

Other floods are due to rivers rising over or breaking natural and artificial banks. Such floods usually occur when the rainfall is heavy or snow melts rapidly, and either (*a*) the ground is saturated, or (*b*) frozen or without vegetation-cover, or (*c*) the volume of the river in its

FIG. 63. — The city of Black River Falls, Wis., before and after the flood in 1911.

lower course is already great. Several of the greatest Mississippi river floods, which have come on the average about once in 6 years, occurred in 1882, 1897, 1903 and 1912, the one reaching the highest stage and having the greatest duration being that of 1912, when the cities of Vicksburg, New Orleans, and Memphis suffered most.

The rise in spring level in the Ohio, upper Mississippi, and Missouri rivers normally comes in different months, but in 1912 the rise of the Ohio was late. Excessive rainfall in the Ohio and lower Mississippi basins was the chief cause of the 1912 flood, but to this three things should be added: (*a*) the lateness of the Ohio rise in 1912, (*b*) the Missouri flood, caused by melting snow, (*c*) the heavy local rains in the lower Mississippi basin. This 1912 flood rendered about 30,000 people homeless in the region north of Louisiana. In that state 350,000 people were affected by the flood, a third of them suffering severe losses. Flood warnings by the U. S. Weather Bureau are now preventing practically all loss of life during spring floods in the lower Mississippi. Careful estimates show that the destruction of property amounted to 27 million dollars, the loss of crops nearly 35 million dollars, damage to farm land nearly half a million dollars, and losses through suspension of business almost 16 million dollars, making a total loss of about 79 million dollars through this one flood.

River Volume and Velocity

Volume. — The volume of a river depends upon the water supply; but the depth of the river depends upon both the amount supplied and the rate at which it can flow along the channel.

There is much variability in river volume, as already explained. Some streams have always a small volume, some always a large volume, but most have a variable volume, fluctuating with the supply. Were it not for the supply of underground water, the stream volume would vary far more than it does; but, even with this aid toward regulation of volume, the great majority of streams experience wide fluctuations from time to time. Those whose source of supply is mainly from springs, or which emerge from lakes, are least subject to fluctuation in volume; while those whose supply is in large part from run-off of rain-water or melting snow experience the greatest variation. This is especially true on slopes denuded of vegetation or surfaces that are relatively impervious, as bare rock slopes or frozen ground.

Illustrations of Variations of Volume. — Since under normal conditions from one-third to one-fourth of the rainfall is discharged by rivers, while the balance is either evaporated, or taken up by plants, or stored underground, it follows that as the rainfall varies, the volume of the streams must be subject to notable fluctuations. The Seine, for instance, which normally flows through Paris as a quiet, well-regulated stream, may rise 20 feet in periods of heavy rain or melting snow, and even flood the lower portions of the city, as it did in 1910. The Hoang Ho in China may rise 40 feet in times of flood and, breaking through its embankments, spread over the surrounding country in a devastating current 30 miles wide and from 10 to 20 feet deep in its deepest part. The Mississippi floods have already been described.

Periodic Variations of Volume. — Many rivers are subject to periodic variations in volume. This is true, for example, of rivers whose sources are among snow-covered mountains, like the Colorado, or the Ganges, which commence to rise when the snows of the mountains begin to melt in spring. Every April the Ganges begins to rise, and continues to do so until the surrounding plains are transformed to a lake 32 feet deep. The Nile is flooded every summer during the rainy season in the Abyssinian headwaters, and the river rises 23 or 24 feet at Cairo, and floods the delta plain below that city, irrigating and fertilizing the soil and giving rise to a vast oasis in the desert region, on which a dense population has dwelt for thousands of years, where one of our earliest civilizations developed.

Velocity. — The velocity of a river is primarily dependent upon the slope of its bed; and, since the slope commonly decreases from headwaters to mouth, the velocity normally diminishes in the same direction. In some parts of certain streams the slope is vertical, as at Niagara Falls, and there the velocity attains its maximum. Such conditions are, however, exceptional, and good-sized rivers rarely have a very rapid slope. The average slope of the larger rivers of the world is probably not over 2 feet per mile, and navigable rivers do not often attain a slope greater than 10 inches per mile.

Illustrations of Variations of Slope. — Some, however, have a much lower slope, such as the Volga, with its average slope of but 2 inches per mile. The Colorado, which descends from a lofty mountain range, has an average slope of but 7.72 feet per mile, and for a large part of its course it rushes along with torrential velocity. The Amazon descends at the rate of $\frac{1}{8}$ inch to the mile in the lower 500 miles of its course. But such an average does not represent the actual conditions, for the slope of the stream bed is gentle in places, and steep in others, so that there are stretches of lakelike water and stretches of torrential flow.

Variations of Velocity with Volume. — Velocity of river water, however, is not solely dependent upon slope, for, even without change of slope, the velocity becomes greater with increase in volume. Therefore whenever a river rises in flood its velocity is greatly increased as well as its volume. The rate of flow of a stream, accordingly, varies from time to time as the volume varies. When the volume dwindles, even a steeply sloping stream may have a fairly quiet flow; but with the coming of a flood it is transformed to a raging torrent. A moderate river current is about $1\frac{1}{2}$ miles per hour, but torrents on steep slopes may attain a velocity of 18 or 20 miles per hour.

Variations in Different Parts of Stream Course. — There is not a uniform velocity throughout a river at a given cross-section, any more than there is along a longitudinal section. The velocity is normally greatest in the centre and least along the margins, where the shallowness and friction diminish the rate of flow. It diminishes from near the surface to the bottom, where friction also tends to diminish the velocity. There is also a relation between velocity and the nature of the channel. A smooth, regular channel permits more rapid flow than an irregular channel; and where water is forced from a broader to a narrower channel the velocity increases, as it also does where a tributary pours water into a channel which is not proportionately larger. By irregularities in the stream channel minor currents and eddies are set up which interfere with the general forward movement of the water, and may even give rise to local up-stream movements.

These variations in volume and velocity of river water have an important bearing upon the work of rivers, both in transportation of sediment and in excavation of river valleys.

The Mineral Load of Rivers

Visible and Invisible Load. — All running water on the earth is carrying a load of mineral matter, though the load varies greatly from one stream to another, and from time to time even in the same streams. This mineral load is carried partly in solution, partly in fragmental form. The former is the *chemical* load, which is invisible, the latter, the *mechanical*, which is visible.

Chemical Load. — By far the greater proportion of the chemical load of rivers is supplied by underground water, which, as we have seen, brings to the surface a great variety of mineral substances in solution. No matter what may be the nature of the rock through which the water percolates, it obtains a greater or less quantity of mineral matter, of one or of several kinds, and a large proportion of this the rivers transport to the sea. By analyses of river waters it is known that this dissolved load is great in total quantity. The Thames, for example, transports 548,000 tons of mineral in solution each year, which is equivalent to about 140 tons removed annually from every square mile of limestone in its drainage basin. If removed equally from all parts of the basin it would lower the surface 1 foot in about 13,000 years by solution alone. It is estimated by Reade that the mineral matter carried in solution in river water is the equivalent of about 100 tons for every square mile of land surface in the world. Most of this is doubtless derived from the more soluble rocks, such as limestone, but all rock through which water percolates is supplying some. Naturally, therefore, though the surface is being steadily lowered by the solvent action of water, the rate varies greatly with the kind of rock.

Besides the chemical load contributed by the underground water, there is an addition to the supply obtained by the surface water itself. Every rill and every river may add to the chemical load as it flows over soil or rock. Ordinarily this contribution is slight, and its amount depends upon the composition of the water and the nature of the rocks. Water impure with organic acids will dissolve more than purer water; and river water is often charged with these or other substances that give it solvent power. That the solution of mineral substances is in progress in river beds is well illustrated in limestone regions, where the rock of the river bed is often etched into a series of ridges and hollows by the irregular rate of solution, as in the Niagara River above the falls.

Mechanical Load. — While the chemical load of rivers comes mainly from underground, the mechanical load is essentially a contribution from the surface. Some of it may fall to the river from steep slopes, where it has been dislodged by the pull of gravity upon weathered rocks; some is worn from the river bed by the attrition of the rock fragments against the stream bottom. But by far the greater portion of the mechanical load of rivers is washed into the stream by the multitude of rills and minor tributaries, especially those on steep slopes and in unconsolidated material, and particularly during heavy rains or rapid melting of snows. A source of sediment for some streams is the contribution of rock material from glaciers; but this may be considered an exceptional source, while the others are normal to all rivers.

Transportation of Mechanical Load. — The transportation of this mechanical load is accomplished partly by pushing or rolling the fragments along the river bed, partly by carrying them along bodily in suspension. It is only the lighter fragments that can be carried in suspension, ordinarily clay, though in swift currents even sand may be thus carried. Even the finest clay particles are heavier than water, and will settle when the water is allowed to stand; but in the river current there are eddies which serve to float the fine-grained sediment, as dust is floated in the air. It is not to be inferred that such particles are carried along uniformly, as the dissolved mineral substances are, but rather that there is a constant tendency toward settling to the bottom, so that, if a particle could be traced from a river source to a river mouth it might be found to descend to the bottom and rise in the river again many times on its way, and perhaps even to rest for a long time in a sand bar or other river deposit.

Transportation by Dragging. — Near the bed of a heavily burdened stream the water may be so filled with sediment that the land itself is rapidly changing by the forward gliding of the water-filled sand; and in all sediment-laden streams there is an important movement of the heavier particles by dragging. This transportation is accomplished by the push of the moving water, and since stones lose from one-half to one-third of their weight in water, it is possible for a rapid current to drag along even good-sized stones. The size of a stone that can be moved by a given current depends to a large degree upon its specific gravity and upon its shape, both of these factors depending primarily upon the area exposed to the force of the current. Rounded stones are more easily moved than flattish forms, partly because of the greater surface exposed to the current, and partly because they are more easily rolled along.

Muddiness is evidence that streams are carrying a load, but this muddiness may be checked (*a*) by forested slopes, (*b*) by gentle slopes, and (*c*) by the presence of prevailingly coarse, heavy sediment, which is dragged along the bottom of the stream instead of moving in suspension and thereby clouding the stream.

Relation to Velocity. — A current of half a mile an hour will carry coarse sand, while a current of two miles an hour will move angular stones the size of an egg. The transporting power of the water varies as the sixth power of its velocity, so that if the velocity of the current is doubled the power of transportation is increased 64 times. Consequently swift currents have an exceedingly high transporting power, some being able even to move boulders hundreds of pounds in weight, especially on steep slopes. In torrential waters one can often hear the stones bumping together as they are rolled along the bed.

Velocity has much to do with transportation of the stream load near the headwaters of streams. Here there may be little water and coarse sediment, so that a steep slope and high velocity are necessary for the transportation of the stream load, the coarser part of which will move only by dragging. In the lower course, however, with the large volume of the stream, the bulk of the sediment, which is fine, needs less slope and less velocity in order that it may be carried in suspension.

Eddies and Ripples. — The movement of sediment along the stream bed is not a uniform process, for, owing to the irregularity of the bed, the velocity of the current varies from point to point. As a result there is a concentration of greater energy in some places than in others. A complex series of eddies is introduced, and their activity is often expressed by the excavation of deep holes which vary in position and depth as the velocity varies, or as the cause for the eddy changes. Another form of the concentration of the energy of moving water is the development of ripple marks on which the energy of the current is localized, moving the particles from the up-stream face of the ripple and rolling them into the depression on the down-stream side. As a result of the movement the ripple marks move down-stream, but the general ripple form is preserved. In a shallow, heavily burdened stream one can see the procession of ripple marks as they pass along, their positions being marked by the wavy water surface as it is thrown upward and downward in its passage over the hidden ripple marks. In fording such a stream one can feel the sand or gravel as it glides along; and if the stream bed is abandoned, the wavy ripple marks, a foot or two high, are exposed to view.

Wearing of Transported Material. — By this dragging of rock fragments, large and small, over one another, and over the stream bed there is constant attrition, by which the fragments are ground down and even the hardest rock in the stream bed cut away. It is by this attrition that a part of the finer sediment, which moves down-stream in suspension, is derived. This is also one reason why the size of the fragments borne by a river normally decreases from source to mouth. But another reason is that the river current decreases in velocity toward the mouth and hence the size of particle that can be moved decreases. Nevertheless, if the coarser fragments of the upper part of a stream course were not ground down to size suitable for transportation by the currents of decreasing velocity there would be an accumulation of coarser fragments which are being steadily supplied for transportation.

Variations in Transportation. — The quantity of sediment transported by a river depends partly on the volume and velocity of the water, partly upon the amount of sediment contributed. All of these factors are variable in a given river, which may at one period be clear, limpid water and a little later be transformed to a rushing flood of discolored, sediment-laden water. They also vary from stream to stream. There is every gradation from the vertical fall of water, descending as rapidly as gravity can draw it down, to the stream of barely perceptible current; and from streams of large to those of small volume. There are some streams which are always comparatively free from sediment load, notably those like Niagara, which issue from lakes, in whose quiet waters sediment has settled. Others vary in their sediment load from periods of heavy load to periods of light load or even absence of load. And still others are always heavily sediment-laden, as the Missouri and lower Mississippi are.

Overburdened and Aggrading Streams. — Some streams are so heavily burdened with sediment that they cannot carry it all, and are *overburdened*, as the Platte River is. Such streams are forced to steadily lay down some of their burden in the stream bed, building it up. Such streams, of which the Platte is a typical instance, are said to be *aggrading* streams, in contrast to those which are cutting into their bed or are *degrading*.

Amounts of Material Transported. — Heavily charged streams are efficient agents of transportation of the rock waste of the land. The Mississippi, for instance, pours into the Gulf of Mexico 19,500,000,000,000 cubic feet of water each year, which carries with it about 812,500,000,000 pounds of rock fragments. This vast amount of sediment if collected would form a prism a mile square, and 268 feet high. If the rock material poured into the Gulf of Mexico by the Mississippi River each year were removed equally from all parts of the drainage area, the entire surface would be lowered about one foot in 6000 years. It is estimated that the rate of lowering of the drainage basin of the Hoang Ho is one foot in about 1464 years; of the Po, one foot in 729 years; and of the Danube, one foot in 6846 years.

Processes of River Erosion

Corrasion and Corrosion. — River water is competent to remove unconsolidated material from its bed up to the size of fragments which can be dragged along during its periods of greatest velocity. River water is competent also to remove rock material in solution. Therefore even clear water can perform some work of degradation by mechanical means or *corrasion* in unconsolidated rock, by chemical means or *corrosion* in solid rock. The rate of corrosion is dependent upon the volume of water, the composition of the water, and the nature of the rock. Even in such a soluble rock as limestone, however, the rate of excavation by the process of corrosion is exceedingly slow.

Sediment furnishes River Tools. — The mechanical or corrasive work, while greatly influenced by the volume and velocity of the water and the nature of the rock, is primarily dependent upon the sediment load which the river current drags along its bed. Sediment therefore furnishes tools, used by running water in its work of excavation. If the stream has little sediment, its rate of work is necessarily slow in all but unconsolidated rocks; and if, on the other hand, it has a heavy sediment burden, it may be forced to aggrade its bed and, therefore, be prevented from using its tools in deepening its channel. But streams with abundant sediment, though with no more than they can transport, are competent to degrade their beds even in the hardest rocks. For, as the sediment is dragged over the rock, it chips and grinds off particles and moves them down-stream.

Agents of Stream Erosion. — The combined work of corrasion and corrosion, together with the accompanying transportation, is *erosion.* While the work is primarily that of solution and mechanical wear by the movement of sediment over the bed, there are some supplementary phenomena modifying the process of erosion. Some of these, such as the influence of the nature of the rock, the variation in volume and velocity, and the difference in chemical composition of the river water, have already been mentioned. Another is the effect of weathering upon the bed of a stream during intervals of low water when it is exposed to the air. And still another of much importance in regions of frost is the influence of ice.

The Work of River Ice. — The formation of ice greatly modifies the volume of a stream, first by temporarily locking up some of the water, and then, on melting, by giving it back to the stream, often in considerable volumes. When the river freezes to the bottom, or when ground ice forms on the river bed, the same disruptive effect may be caused in the rock as results from frost action in the process of weathering. As the river increases in volume the ice may lift rock fragments from the bed and float them on down-stream, even carrying much larger fragments than the river unaided can transport. Now and then the ice blocks form a dam, ponding back the river water and causing serious floods above the dam, and, if it breaks, giving rise to a temporary great increase in the river volume below the dam, by which, in a brief interval, much work of erosion may be performed. Such ice jams, or ice gorges, do much damage to life and property (Fig. 64).

Rapid and Slow Erosion. — In its work of erosion, river water does not work uniformly either from the standpoint of time or of place; for at times the rate of work is far more rapid than at others, and there is also notable variation from point to point along the river bed. For weeks or months a stream may flow leisurely, with limpid current, accomplishing little or no work of erosion; and then it may be transformed to a flood of rapidly rushing, sediment-laden water. Temporarily the river then becomes a vigorous agent of erosion, in a day or two perhaps accomplishing more work than in the entire preceding year.

FIG. 64. — River ice in a spring flood on the Susquehanna River. (Hoyt, U. S. Geol. Survey.)

Even in streams that are always armed with cutting tools, and that always flow with considerable velocity, there are periods when an increased volume gives such added velocity that their rate of erosion is greatly increased. In the arid southwest the intermittent streams sometimes spread out in *sheetfloods*, a current perhaps a mile wide and 1 or 2 feet deep.

Pot Hole Action. — Owing to the eddies in river currents and to the irregular rate at which the bed is worn down in rocks of different degrees of resistance, there is a tendency toward the greater concentration of the energy of the flowing water at certain points, thus giving rise to local deepening. Once a depression is excavated, the added velocity which the increased slope induces tends toward still further deepening. The operation of this process is most typically illustrated in the development of *pot holes*, which abound in the rock floors of rapidly flowing streams. In their inception the pot holes may be due to irregular solution, to eddying currents, to the presence of joint planes in the rock, to the more rapid wearing away of weaker portions of the rock floor, or to the falling of water in a waterfall. Whatever the cause for the first stage of the depression, once it is formed the tendency is for it to enlarge under the influence of the increased velocity of the water falling into it, the swirling of the current in the depression, and usually, also, by the grinding of rock fragments caught in the depression and whirled about in the pot hole eddy.

By this action a hole a few inches or a few feet in depth, and varying similarly in width, is quickly excavated in the rock. It is usually enlarged below by the grinding action of the stones which the eddy whirls around, assuming the kettle shape from which the name pot hole is derived. There is a limit to the depth to which a pot hole may be excavated, for, as it grows deeper and the volume of water in it becomes greater, its eddy becomes slower and less effective; or, before this stage is reached, the current may be deflected and pot hole work cease at that point, though perhaps beginning at another.

Local Concentration. — Such local concentration of energy of the river water is an important factor in stream bed deepening, for, although the pot hole is only local, the process is operating at numerous points and is shifting from point to point, while every now and then the walls of contiguous pot holes give way, thus increasing the continuous area of deepening. To concentrate upon a given portion of a stream bed, or at times even the whole volume of a stream with that maximum velocity which comes with vertical fall, necessarily means a great local work of excavation. And probably by such local concentration the average work of corrosion along a stream bed is greater than if the energy of the stream were equally applied to all parts of the channel. Not always are perfect pot holes produced by such concentration, but the process is similar, even though time or other factors do not permit the perfect form to develop.

The Formation of Gorges and Canyons

Youthful Steep-sided Valleys. — When a stream is steadily cutting into its bed, it sinks itself more and more deeply below the general surface of the land until finally it may be enclosed between lofty, steeply rising walls. Such a precipitously walled valley is called a *gorge,* gulch, or ravine, or, in western United States, in many cases, a *canyon.* There is no hard-and-fast line that can be drawn between a gorge and a canyon, for both are due to the rapid down-cutting of a stream bed, and both are narrow, steeply walled valleys sunk below the general surface of the country. A canyon may perhaps be considered to be a larger form of a gorge such as is characteristically excavated in a region of high plateaus, like Mexico and southwestern United States. But in common usage even this distinction is not followed.

Vertical Deepening. — The primary cause of the gorge or canyon is the erosion by water as it wears away the rock along its line of flow. If no other process than this were at work, the gorge would have no greater width than the stream, and there are gorges in which this condition is actually present for at least a part of their length or depth. There are, however, two other processes which tend to widen the gorge at the same time that the river erosion is deepening it.

Lateral Cutting. — One of these is the lateral swinging of the stream, or eddies deflected toward the side of the stream, by which some of the erosive energy of the running water is employed in lateral excavation. Where the rocks are weak, as in unconsolidated beds, the lateral erosion is an important aid in broadening valleys; it is also effective in consolidated rocks, but to a far less degree. Valleys are broadened more, on the whole, by undercutting than through the aid of weak strata. In some cases, where the rocks are held firmly together, the effect of the lateral erosion has merely resulted in causing overhanging cliffs, or in giving the gorge a diagonal or curving form, so that from its bottom one looks upward to a rock roof, and cannot see the sky. Naturally, such a condition cannot be enduring, for gravity and weathering will in time destroy such an unstable valley wall. Consequently, when this condition is present, we may be sure that the work of excavation has been both recent and rapid, and that the gorge is young.

Gorges Broadened by Weathering. — The second process, by which the narrow gorge due to vertical erosion is broadened, is by weathering. A steep rock slope exposed to the air is normally a place of rapid weathering; and if there is a stream at its base to remove the weathered products, the wasting back of such cliff should proceed apace. When, therefore, a gorge is found in which the walls are still precipitous, it may be confidently inferred that the gorge is young in the geological sense; for, if it had long been exposed, it would be broadened and rounded by the operation of the agencies of weathering.

Both lateral swinging and weathering are at work at all times upon the walls of a gorge, from the moment the stream first sinks its channel below the surface. An indication of the truth of this statement is commonly to be observed in gorges, for they are usually broader at the top, where weathering has been longest at work, than they are at the bottom, where there has been little time for the operation of weathering. And gorges in weak, easily weathered rocks have a more flaring form than those in the more durable rocks. The fact that gorges are no broader than they are testifies not only to the youthfulness of this land form, but also to the fact that the vertical erosion along the bed of a vigorous stream is a more rapid process than weathering, even on steep slopes.

Gorges Indicate Youth. — The development of gorges is possible only where there is opportunity for a rapid flow of water, and such opportunities are most commonly found among mountains and plateaus where there is a sufficient elevation to give the slope for the necessary velocity. It is possible also only where these processes have been begun recently in the geological sense; consequently it is among mountains and plateaus of recent development that gorges and canyons are most abundant, though gorges may develop in other situations where a favourable condition of slope has been recently introduced.

The process of gorge excavation is that of river work in general, as outlined in the preceding pages. By corrosion and corrasion, by variation in volume and sediment load, and by concentration of energy in pot hole work and in waterfalls, the rock in the river bed is worn away. Usually the processes are still in operation, and may be observed, though even such rapid work is slow from the standpoint of the human time measure. It is only in the geological sense that it may be considered rapid. Doubtless careful measurements would show changes from year to year, but casual observation, even during a lifetime, might fail to note any change.

The Limitation by Baselevel. — Even the gorge deepening must reach an end, for, when the flow becomes so gentle that the sediment load is no longer dragged over the bed as a tool of erosion, deepening must cease. At no point in its course can the stream lower its valley appreciably below the level of its mouth; and this level is, for the stream, its *baselevel*. The ocean surface is the great baselevel, but individual streams may have temporary baselevels well above sea level, such, for example, as a lake. At the mouth of a stream the bed may be very slightly below baselevel, as in the Rhone where it enters Lake Geneva. Nevertheless the baselevel absolutely controls the depth of cutting by streams. Another temporary baselevel is a main stream, below which no part of the tributary valley may be cut so long as the level of the stream mouth is maintained. A temporary baselevel may even exist below sea level, where a stream is tributary to a part of the land that lies below sea level, like the depression in which the Dead Sea lies.

The Grade of Streams. — While at its mouth a river may lower its valley bottom to the baselevel, this cannot be done for any great

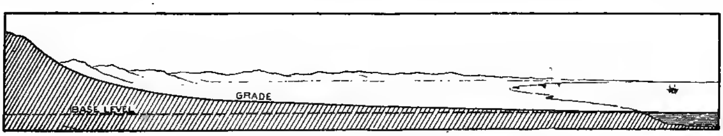


FIG. 65. — Relation of grade to baselevel.

distance above the mouth, since the water must have a slope over which to flow and transport its sediment load. The lowest slope over which a river can transport its sediment load may be called its *grade*, or gradient. This grade is a curve, flattest near the mouth where the volume of the stream is greatest, but increasing in steepness toward the headwaters where the volume is least (Fig. 65).

By its erosive work a stream is tending toward the attainment of a perfect grade, and the development of a gorge valley is an early step in this process, in which the stream is so far from flowing with a perfect grade that it can cut rapidly along its bed. As the graded condition is more nearly approached, the rate of erosive work diminishes and ultimately practically ceases. But the grade is not to be considered a definite curve that, once established, is forever fixed; for, since it is the lowest slope over which the river volume can transport the sediment load, if the volume increases without change in the sediment load, the grade can be lowered; or, if the sediment load increases without change in volume, the grade must be increased. In the first case the grade is rectified by degradation; in the second, by aggradation. It commonly happens that a grade established under one set of conditions must later be altered to meet newly developed conditions.

Widening of Graded Streams. — As the perfect grade is approached, the rate of down-cutting along the river bed becomes so slow that finally the rate of weathering is in excess of the rate of down-cutting. And ultimately, when further down-cutting is at an end, weathering is the main factor in valley formation. During these stages the valley sides waste away, the valley broadens, the slopes lose their steepness, and the gorge form is destroyed. This process, however, is a slow one, and is attained only after the lapse of sufficient time for the operation of the agencies of weathering. Many times as long a period is required for the rounding of the valley slopes as is required for the formation of the gorge. In this process the river is still an important agent, for upon it falls the task of removing the rock materials which weathering supplies, and which come to it from the multitude of rain-born rills and other stream courses that develop upon the valley sides. Up to a certain point the river works directly also by its lateral swinging and consequent removal of material by lateral erosion even after vertical erosion has ceased.

Grand Canyon of the Colorado

The Most Wonderful Work of Nature. — Of all the gorges and canyons of the world, and perhaps of all works of nature the most wonderful example, is the Grand Canyon of the Colorado. The Colorado River, which has carved this canyon (Fig. 66), is made by the union of two tributaries, the Grand and Green. It has a total length of about 2000 miles, and drains an area of about 225,000 square miles. Having its source among the lofty ranges of the Rocky Mountains, this river has an abundant supply of water and plenty of sediment for cutting tools. On its way to the sea the river must cross a lofty plateau, in places over 8000 feet high, and so recently elevated that the river has not yet been able to cut down to grade. Accordingly the river has still a steep slope (7.72 feet per mile) which insures high velocity.

Factors Favouring Canyon Cutting. — The Colorado River has all the favourable factors for pronounced canyon cutting: (*a*) large volume, (*b*) high velocity, (*c*) an abundance but not a superabundance of sediment, (*d*) a great thickness of rock to cut into before grade can be reached. Still a fifth factor of importance is the aridity of the

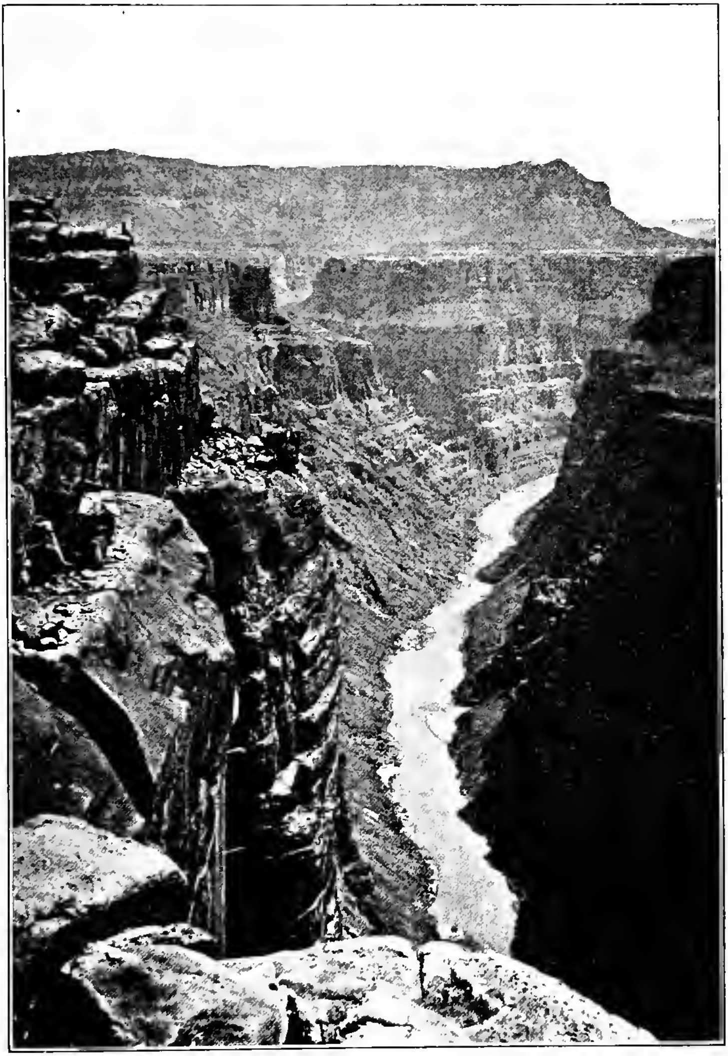


Fig. 66. — The Grand Canyon of the Colorado, with deltas of tributary streams. (Hillers, U. S. Geol. Survey.)

climate throughout the canyon section, as a result of which the canyon form tends to be preserved because of the slowness of the operation of the agencies of weathering.

Canyon cutting is necessary, as may be estimated in the case of a stream flowing 200 miles across a plateau 2000 feet high. If it was on the surface of the plateau at one side and had a grade as steep as the Colorado, nearly 8 feet per mile, it would necessarily incise a canyon 1600 feet deep by the time it had crossed to the other side of the plateau.

Relationship to Rock Strata. — In crossing the plateau the river has entrenched itself in a canyon for a distance of between 200 and 300 miles and to a depth varying from a few hundred feet to 6000 feet. As the river crosses different sets of rock strata the form of its canyon varies, and different names are given to the several parts. Where

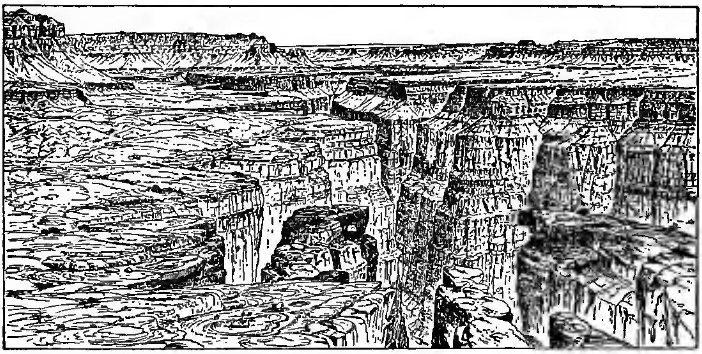


Fig. 67. — Cliffs and slopes due to resistant and weak strata at the Colorado Canyon. (Holmes.)

the rocks are massive, the canyon is narrow and the walls rise precipitously with little variation; but where the beds vary in texture, denudation has etched them out at varying rates, and there the canyon walls are wonderfully sculptured (Fig. 67).

The sculpturing of the canyon walls is along both horizontal and vertical planes. The horizontal sculpturing is due to the varying degree of resistance to weathering of the more or less horizontal strata, giving rise to a series of steps in the canyon walls with precipices where resistant strata outcrop, and more gentle slopes where the weaker beds lie. Since these strata are variously coloured, they give rise to a gorgeous, though gaudy, colour effect, as well as to marvellous sculpturing. Vertically the canyon walls are gashed by a multitude of ravines, gorges, and canyons, where running water has cut into the plateau as the rain-water has hurried down the canyon sides to the river; and between these are pillars, minarets, ridges, and table-topped spurs.

Evidences of Origin. — As one looks down upon the maze of sculptured rock forms from the plateau edge it seems hardly possible that running water and weathering could have performed such a vast work; but, on descending to the canyon bottom, the result seems less difficult of conception. The steep cliffs are seen to be ragged through weathering, and here and there one sees places from which masses of rock have only recently fallen. In the bottom of the lateral canyons are seen huge rock fragments, which the floods of occasional rains are moving down the steep slopes of the canyon bed to the main river. And the river itself, seemingly a silvery thread when viewed from the plateau top, is found to be a rushing torrent, discolored with the heavy burden of sediment which it is hurrying on toward the sea. All the necessary processes are plainly visible; and all that one needs supply to attain even such a grand result is the element of time for the effective operation of these processes. Of that there has surely been sufficient.

The Canyon as a Barrier. — The great gash which the Colorado River has cut in the plateau forms an almost insuperable barrier to travel. Even though at the top it is ten or twelve miles wide in places, thus giving an average slope of no great steepness, it is so sculptured, and there are so many precipices where resistant rocks outcrop, that only with the greatest difficulty is it possible to get to the bottom at certain favourable spots. Trails to the canyon bottom are maintained at the points tourists visit, but elsewhere the bed of the canyon is quite inaccessible. No road crosses this canyon, and a person living on one side would need to make a journey of two or three hundred miles to reach a spot only eight miles away on the opposite side of the canyon. The Colorado Canyon is one of the most perfect barriers to travel in the world (Pl. VIII).

While the Colorado Canyon is the grandest of the type, it is, in reality, but one of a class. There are hundreds of similar, though smaller, canyons in western United States, and in other regions of high plateaus, while gorges, the smaller forms of the same valley type, occur by the thousands in plateaus and mountains, as well as elsewhere where favourable conditions exist.

The Formation of Waterfalls

Rapids, Waterfalls, and Cataracts. — Where the bed of a stream steepens abruptly, the current quickens, giving rise to a *rapid*, or, if the slope becomes vertical, to a *waterfall*. There is no distinct line that can be drawn between a waterfall and a rapid, for they grade into one another, and what are really rapids under the terms of the preceding sentence are sometimes called waterfalls. The term *cascade* is often applied to a small waterfall, and *cataract* to a large one like Niagara.

Weak and Resistant Rock Layers. — Waterfalls and rapids normally develop in a stream which is cutting into its bed, because, in its exca-

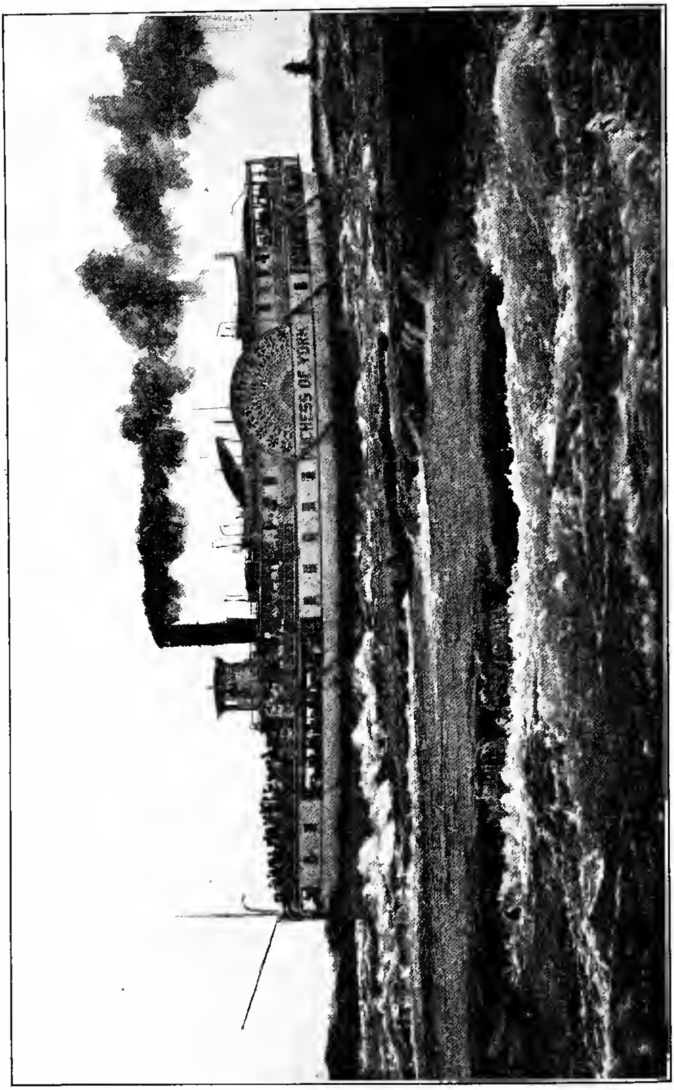


Fig. 68. — Steamer in Lachine Rapids of St. Lawrence River near Montreal.

vation, it finds opportunity for more rapid work in some places than in others. Among the conditions which give rise to this opportunity by far the most common is the difference in resistance of the strata, and especially where the stream is cutting into strata that are horizontal or approximately so. If we assume, what is common, a series of strata of different kinds, lying approximately horizontal, and a stream flowing over and sinking its bed into them, the layers will be cut into one by one. If one layer of rock is fairly resistant, and the one next below is less hard, the stream will find it easier to cut away the lower than the upper one. Since the stream must have a slope, while the strata are horizontal, this weaker bed will be first reached in the lower course of the stream, while higher up the course the stream will still be flowing on the resistant upper layer and cutting into it.

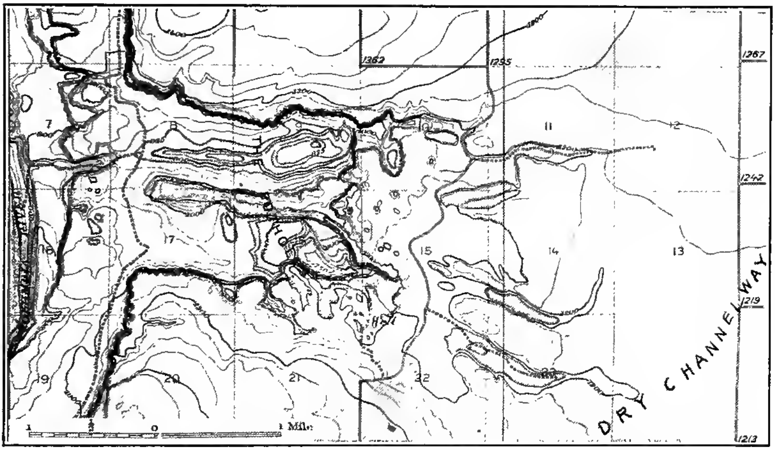


FIG. 69.—Abandoned waterfall in Washington. For location see Fig. 337. (Quincy Quadrangle, U. S. Geol. Survey.)

But since the stream cuts more rapidly in the weak layer, which it has discovered, than in the resistant layer, it will cause an abrupt increase in the slope of the bed at the point where it leaves the ledge which is holding it back. There either a waterfall or a rapid will develop, according to the extent of the difference of the stream excavation in the two layers. If the difference in resistance to stream erosion by the weak and resistant layers is great, there may be a high waterfall; and, if there is also a great volume of water, there may be a veritable cataract. If, on the other hand, the difference between the layers is but slight, or if the layers are thin, there will be only a small fall, or perhaps only a rapid.

Relationship to Pot Holes. — Once an increase in slope of the stream bed is introduced, its further development is made easier by reason of the increased velocity of the water at the point of fall. Here pot hole action commonly aids matters, for the falling water excavates a hole at the base of the fall, and the vertical distance through which the water falls is considerably increased by this action. The formation of the pot hole also aids in causing the waterfall to recede, for, as the swirling waters excavate beneath the resistant layer, it is undermined, and its front recedes. But although the fall recedes, it is not destroyed, for the cause remains; therefore the fall gradually migrates up-stream.

Forms of Waterfalls. — Rapids and falls are common phenomena in the beds of streams which are cutting downward into the rocks. There are often a succession of these as the water leaps from one ledge of hard rock after another. They are sometimes perfectly straight across the face, but most commonly their outline is irregular, for the water, in cutting through the resistant layer to which they are due, does so irregularly, finding a joint plane here or there, or for some other reason concentrating the current at one part of the fall more than at another (Fig. 69).

Waterfalls only in Youthful Streams. — Since waterfalls depend for their existence upon an increase in the slope of the stream bed they cannot exist in graded rivers; for there the river bed is everywhere reduced to the lowest slope down which the sediment load can be transported. Nor can any new falls be developed in such a stream, since it is no longer cutting into its bed. Therefore waterfalls are phenomena of the early stages of valley development, being really features of youth, like the gorges and canyons with which they are so commonly associated.

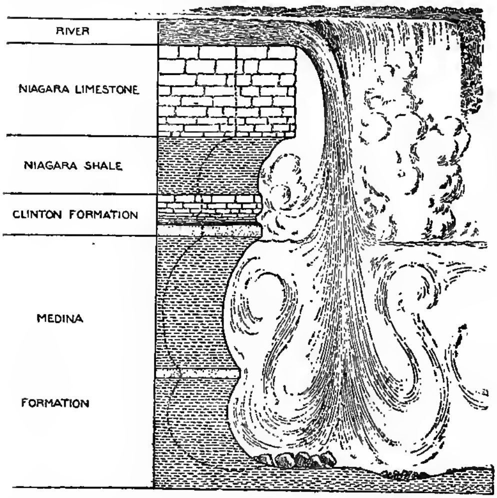


Fig. 70. — Relation of Niagara to limestone and shale. (Modified from Gilbert's diagram.)

Niagara as a Type of Waterfall

Relationship to Niagara Limestone. — Among waterfalls dependent upon irregular excavation in essentially horizontal strata, Niagara is easily the most noted and grandest. The cataract of Niagara is precipitated over a thick bed of limestone, called the Niagara limestone (or Lockport dolomite), which at the falls has a thickness of from 60 to 80 feet, and beneath which are strata of shale and sandy layers. The vast volume of water tumbles vertically through a distance of nearly 160 feet, thus becoming an engine of enormous power, by means of which the shales and sandstones are readily ground away, thus undermining the thick

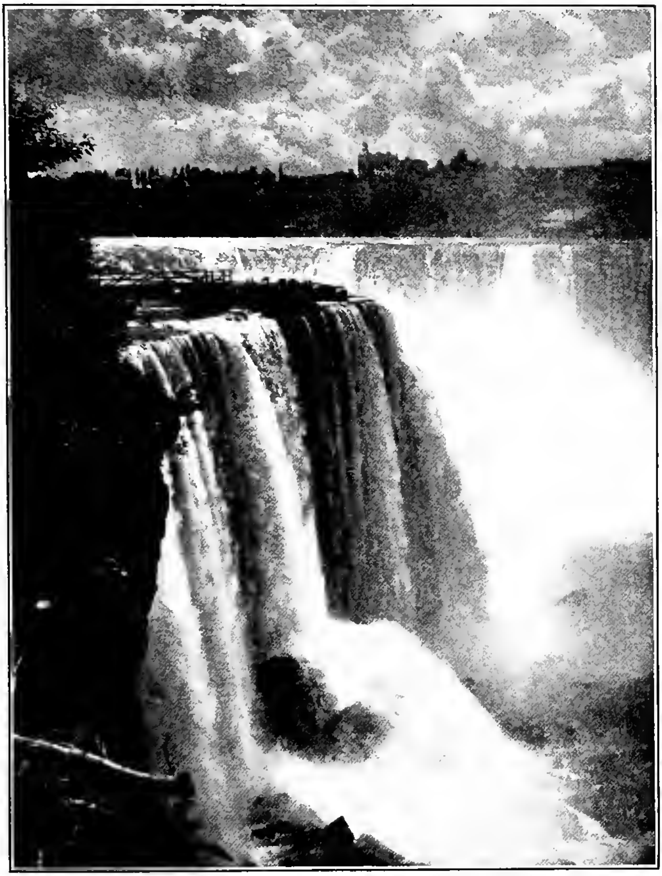


FIG. 71.—The two cataracts at Niagara. American Fall in the foreground.

limestone. Every now and then a block of this limestone falls away and thus the cataract recedes (Fig. 70).

Method of Recession. — The process of fall recession at Niagara is primarily the result of pot hole action, for beneath the cataract a deep hole is excavated in which the water swirls about in a great eddy, carrying with it the limestone blocks that tumble from the crest of the fall, and with them grinding away the rock from beneath the limestone. Supplementary to this major cause are other processes as follows: (*a*) solution, by which some of the rock material is removed by the falling water; (*b*) frost and ice action, by which pieces of rock are loosened and removed; and (*c*) contraction and expansion of air under the varying impulse of the falling water.

The Two Cataracts. — Niagara Falls consist of two cataracts because the current of the river is split by an island in its course, — Goat

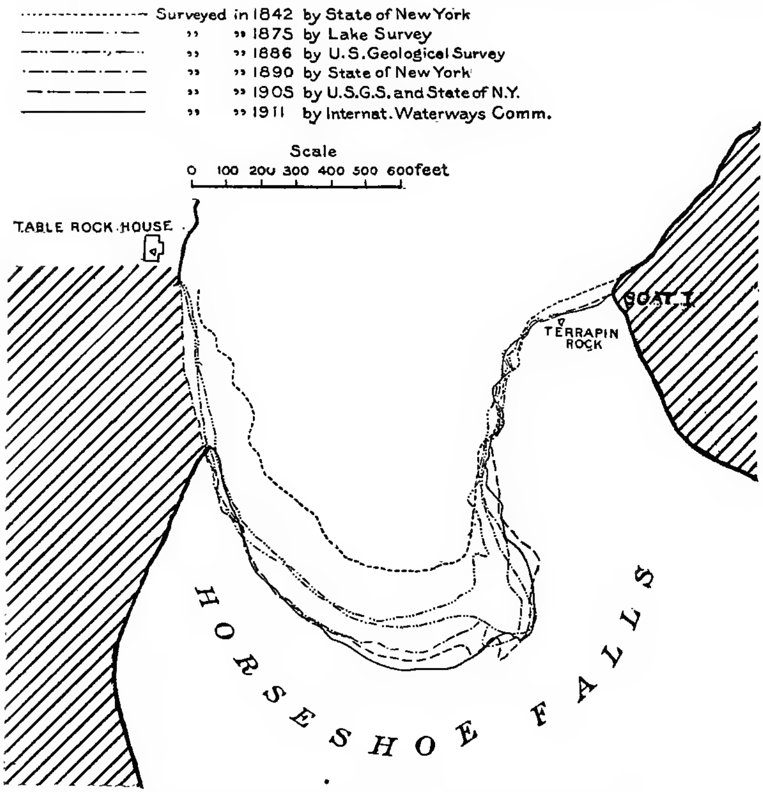


FIG. 72. — Successive crests of Niagara. (After Gilbert and Taylor.)

Island. The larger volume, 95 per cent, flows on the Canadian side of Goat Island, giving rise to the Horseshoe or Canadian Fall, while the lesser volume gives rise to the much smaller American Fall (Fig. 71).

Slow Recession of American Fall. — The volume of water that passes over the American Fall is so slight, and is distributed over so broad an area, that no pot hole is developed at its base; and the limestone blocks that have fallen from the crest of the cataract have not been ground up and removed, but remain like a talus of huge blocks. Upon these the falling water dashes, and over and between them it rushes. Because of the small volume of water and the protection to the base afforded by the limestone blocks, the American Fall is receding very slowly, — by measurements between 1827 and 1905 the rate is determined as less than 3 inches per year.

Rapid Recession of Canadian Fall. — In the Canadian Fall, on the other hand, a vast volume of water is discharged, it being estimated that the average depth of water at the crest of the falls is four feet, while at the central part the depth is twenty feet. It not only disposes of the falling limestone, but, as already stated, undercuts the base of the falls. Measurements between 1842 and 1911 show that the rate of recession of this fall is about 5 feet a year. At the point of greatest depth of water it is most rapid. Owing to this increase in rate of recession toward the centre of the cataract, the Canadian Fall has a horseshoe shape, and is often called the Horseshoe Fall. The maximum average rate at which the fall is receding at the apex of the horseshoe is the rate at which the fall as a whole is receding, for the lesser rate on the side of the horseshoe results merely in broadening the gorge which the receding of the fall is causing (Figs. 72, 73).

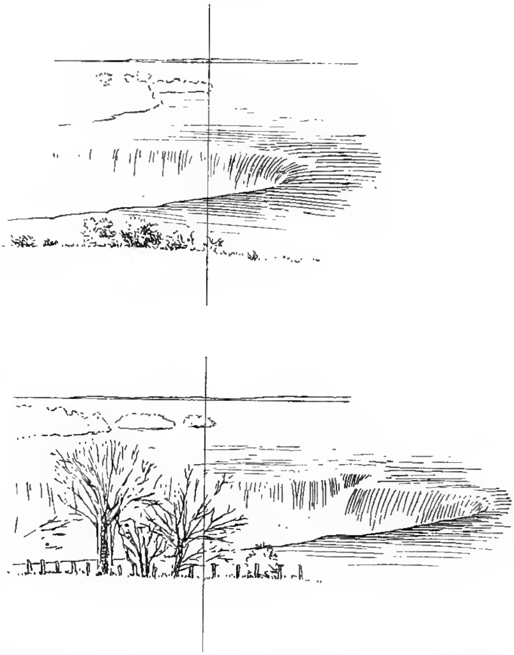


FIG. 73. — Comparison of a camera lucida sketch of the Horseshoe Fall in 1827 with a photograph from the same point in 1905. (After Gilbert.)

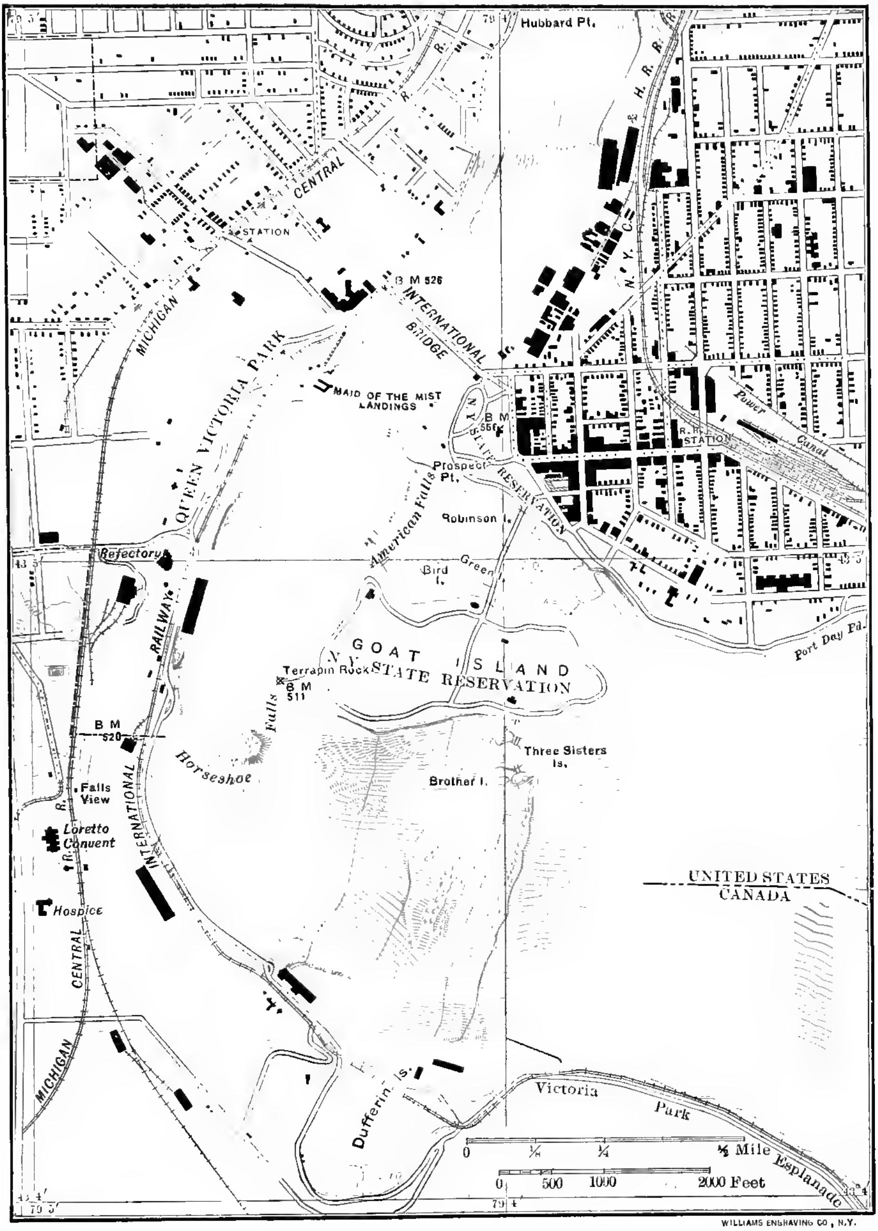
HISTORY OF NIAGARA FALLS

The Two Plains near the Niagara. — Niagara River came into being at the close of the Glacial Period, when the retreating ice sheet uncovered the region between Lakes Erie and Ontario, and the outflow of the former lake sought a way to the latter. The surface of the country between these two lakes consists of two plains, one in which Lake Erie lies, the other bordering Lake Ontario. The two plains are separated by a cliff, or *escarpment*, about 200 feet high, determined by the outcrop of the Niagara limestone which underlies the Erie plain in a nearly horizontal sheet with a southward dip of about 35 feet per mile. At the escarpment the limestone is but 20 feet thick. As the limestone dips into the earth, more and more of it is left, so that it is 60 to 80 feet thick at the falls, and a short distance farther south its total thickness is about 150 feet.

The Original Cataract. — The great volume of water that issued from the glacial predecessor of Lake Erie flowed in a broad course on the surface of the upper plain, and, on reaching the escarpment, abruptly fell to the level of the Ontario plain. It was one of several such falls, the others being to the east (Fig. 194). Thus the original Niagara, just south of Lewiston and Queenston, was determined by an irregularity in the surface of the land, in consequence of which the stream bed had an abrupt increase in slope. Such a waterfall has been given the name *consequent* fall. At once the falling water began excavating and undermining the limestone to which the escarpment was due, and as it did so the fall began to recede. This recession has continued through the whole length of the Niagara gorge, which is about seven miles long.

Proofs of Seven Mile Recession. — The proof that Niagara Falls has receded seven miles is of several kinds, as follows: (1) the cataract is at present receding at a rapid rate by processes which might easily have been in progress for the necessary length of time; (2) the gorge is a youthful topographic form, such as a recession of the falls would normally produce; (3) banks of the old river which flowed on the surface of the plain before the gorge was cut are still plainly visible, and river gravels with river shells are present there also; (4) at Foster Flats, two-thirds of the way down the gorge, there is an abandoned fall of the same type as the American Fall of to-day, having been abandoned by the more rapid recession of a larger cataract, like the present Horseshoe Fall, which then existed on the American side.

The Time Factor. — Since it seems established that Niagara Falls have retreated throughout the seven miles between the escarpment and the present cataract, and since the rate of present recession is known, it might seem a simple task to determine the length of time required for this recession, and, therefore, to fix the date of the disappearance of the ice of the Glacial Period from this part of North America. As a matter of fact, numerous calculations have been made, some of them as low as 3000 to 12,000 years, while others have reached so high a figure as from 50,000 to 100,000 years. The reason for this difference is the entrance into the problem of a series of factors of unknown value, such, for instance, as (*a*) the increase in thickness of the limestone toward the south, and (*b*), what is more important, the variation



NIAGARA FALLS AND GORGE

The waterfalls separate the broad, shallow river above Goat Island from the deep, narrow gorge below. Contour interval 10 feet. (From Topographic Map of the Niagara Gorge, by the United States Geological Survey and the Canadian Geological Survey.)

in river volume during the closing stages of the Glacial Period, when for a time the upper Great Lakes found other outflows than that through Lake Erie. Five stages of variation in the volume of Niagara are indicated in Figs. 75 and 198.

A third important cause for variation is the fact that, as the cataract receded, it found at the whirlpool a buried gorge of an earlier stream filled with glacial drift. This unconsolidated material it quickly swept out, and therefore, for a time, the rate of recession was far more rapid than normal. Until the full value of each of these three and other variable factors is known, any attempt at a final accurate statement of the time required to excavate the Niagara gorge can possess little value. The estimate of 35,000 years, made by Lyell in 1841 and verified by Taylor in 1913 upon the basis of very careful calculations, is probably essentially correct.

The Future of Niagara. — At the present relative rate of recession of the Canadian and American Falls it can be a matter of but a short period before the water of the American Fall is diverted from its present course. There are, in fact, indications that this is even now in progress; and man, by diverting water for power purposes, is aiding in the process of extinction of the American Fall. If the present conditions persist, as there is every reason to believe they will, the American Fall will become extinct, as that at Foster Flats has become, and the combined waters will form a huge cataract which will continue to recede southward. There will come a limit to its recession, however, for as the limestone dips into the ground, the difference in resistance to which the fall is due will finally disappear. The cataract will then change to a rapid, and perhaps this will be worn down to an even grade. In any event, there can be no recession of Niagara southward till it taps Lake Erie, as some have suggested.

Niagara as an Example of a Young River

Before the Glacial Period there was no valley along the present course of the Niagara. It, therefore, furnishes a good illustration of the work which such a river can perform in a short time and of the resulting valley.

The Broad, Shallow, Upper River. — One of the most notable features of the valley is its abrupt and absolute contrast of form above and below the cataract. Above, for fifteen miles, it is a broad stream with moderate current, excepting at one point where there is a rapid, and again near the crest of the falls where there is another rapid. In this course the stream flows almost on the surface of the plain, having cut away little more than the surface cover of loose glacial deposit. The reason why, notwithstanding its great volume, this large river has not entrenched itself more deeply in the plain is primarily the fact that it bears almost no sediment for use as cutting tools; for the waters have been filtered of sediment in Lake Erie, and no large muddy stream contributes sediment along its course. Where the river crosses a bed of limestone, below Buffalo, and again where it crosses the Niagara limestone, just above the crest of the falls, solution has removed some of the rock in the stream bed, roughening it and increasing its slope so that slight rapids have developed (Fig. 74).

The Deep, Narrow Gorge. — Then comes the mighty plunge of the huge volume of water, which, thus concentrated, is able to remove the shale and sandstone and undermine the limestone. Thence, for about seven miles, the water flows rapidly through a gorge or small canyon, whose depth, including the part below river level, ranges from 390 feet near the falls to 490 feet at the escarpment. Its width is

FIG. 74. — The broad, shallow Niagara River above the falls and the narrow gorge below.

from 725 to 1900 feet (Pl. II). Below the gorge the current is again moderate, and steamboats from Lake Ontario can ascend it to Lewiston. In this part the river has excavated its bed down to the temporary base-level of Lake Ontario, below which it cannot cut so long as the lake exists.

The rapids in the gorge are due to the fact that, with its slight sediment load, the river has not yet been able to cut down to grade. These rapids, together with variations in depth of the water and in width of the gorge (Fig. 75) are associated with the variations in volume, as the outlets of the upper Great Lakes changed during the recession of the ice in the closing stages of the Glacial Period mentioned above.

The Whirlpool. — At one point the gorge bends abruptly at approximately right angles, and in the elbow of the bend is the only part of the gorge which is not rock-walled. This is the site of the buried gorge discovered as the cataract receded; and, since the drift filling at its end has been removed more easily than the rock wall, this elbow has been extended some distance into the buried gorge. Into this the current of the river is directed, and in it the water swirls around in a great eddy, called the Whirlpool. Above the Whirlpool are the most notable rapids in the river, the Whirlpool Rapids, the exact origin of which is not yet determined, though there is some reason for believing them to be due to the presence of large limestone boulders which dropped into their present place from a waterfall which existed here

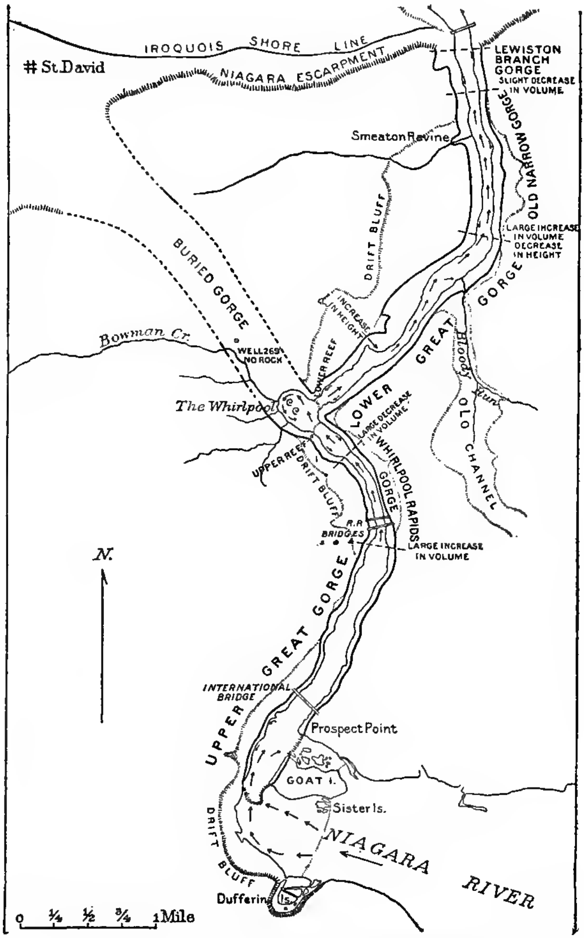


FIG. 75. — Map showing the several divisions of Niagara Gorge. (Taylor.)

before the last advance of the ice when the buried gorge was being formed. If this be the correct interpretation, then the buried gorge which passes out at the end of the whirlpool elbow extended along the site of the present gorge up to the railway bridges, where it terminated in a waterfall that had receded this far when the glacier advanced, extinguished the stream, and filled its gorge with drift. Such an explanation would account not only for the rapids, but also for the narrowness of the gorge at this point, for in this part the Niagara would have had the task merely of sweeping out the glacial drift in a pre-existing gorge of a much smaller stream (Fig. 75).

OTHER TYPES OF WATERFALLS

Falls of Niagara Type Commonest. — The fact that horizontal, or nearly horizontal, strata occupy a large proportion of the land is one reason why falls of the type described in preceding pages are the most common. And another reason is that such falls persist for a long time by recession up-stream, as is so well illustrated in Niagara. There are, however, other causes for waterfalls.

Consequent Waterfalls. — One of these is the presence of a sharp descent on a land surface over which water has only recently been led to flow, — falls consequent upon topography. In the beginning Niagara was a fall of this type, and there are many others in glaciated regions, for the glacier made changes in the topography; it destroyed or altered many preëxisting valleys; and it turned many streams out of their former courses. Waterfalls therefore abound in regions of recent occupation by glaciers, and many of them are of the consequent type, while others have been normally developed, as deflected streams have cut gorges along their courses, and thereby discovered irregularities in rock resistance. Some of these falls are more specifically referred to in the chapters on glacial action.

Influence of Joint Planes. — As streams cut into their beds, any difference in resistance of the rock will give rise to differential cutting. Besides the influence of horizontal beds, there are two other conditions that are noteworthy in fall and rapid development, one the influence of joint planes, the other the influence of inclined beds. It is not uncommonly the case that joint planes may be so spaced as to aid in vertical excavation by running water. At Taughannock Falls, in central New York, for example, the shale rock is so thoroughly cleaved by joint planes that, although the strata are horizontal, great slabs fall away from the cliff face where loosened along the closely set, vertical joint planes. As a result of this vertical cleavage a waterfall 220 feet high has been developed by a small stream which is cutting a gorge in the steep hill slope of Lake Cayuga valley (Fig. 76).

Waterfalls in Lava. — Joint planes aid in the development of waterfalls in many lava rocks, and, by the irregular erosion of the water along the planes, give rise to the irregular outline of such falls. This influence is well illustrated in the Victoria Falls of South Africa and in the Shoshone Falls of Idaho. In both cases the falls are developed in the course of gorge cutting in the lava, in the first case by the Zam-

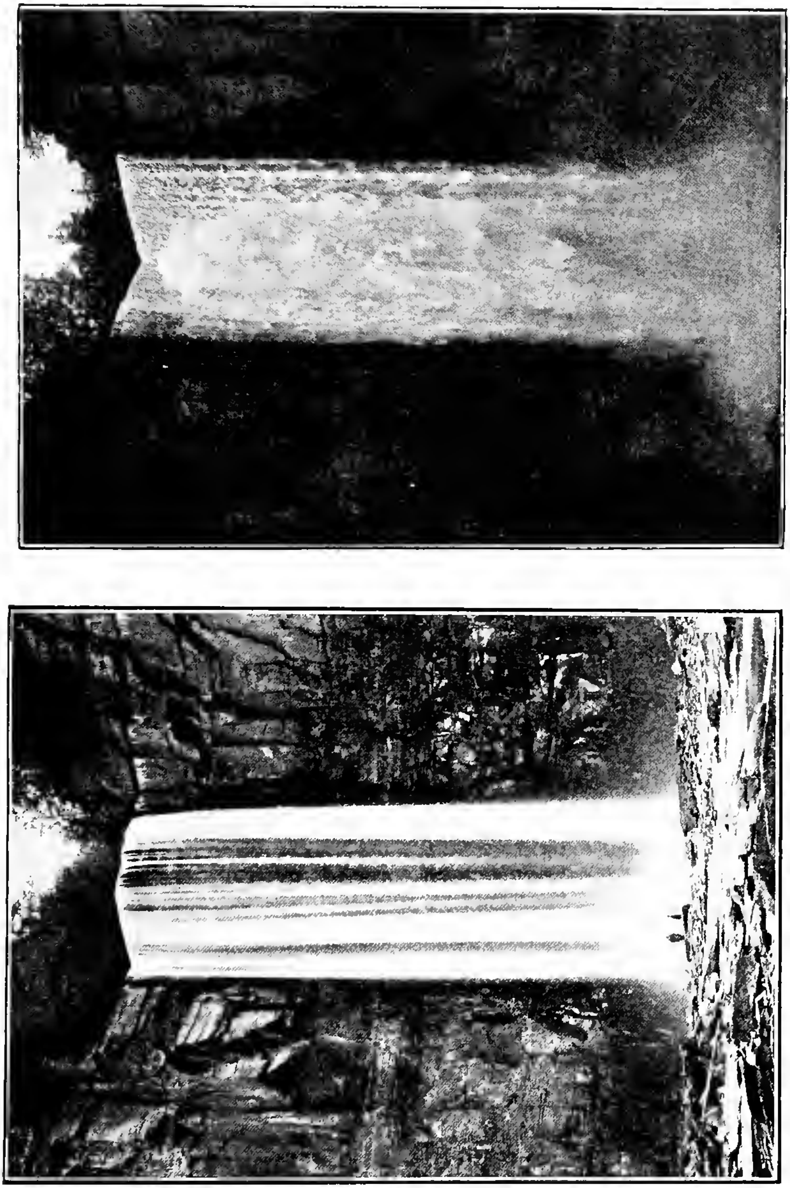


Fig. 76. — Taughannock Falls from the same point at two different dates. The right-hand view shows the fall with its crest having an angle pointing up-stream after a block of rock has fallen. In the earlier, left-hand view the angle at the crest points down-stream.

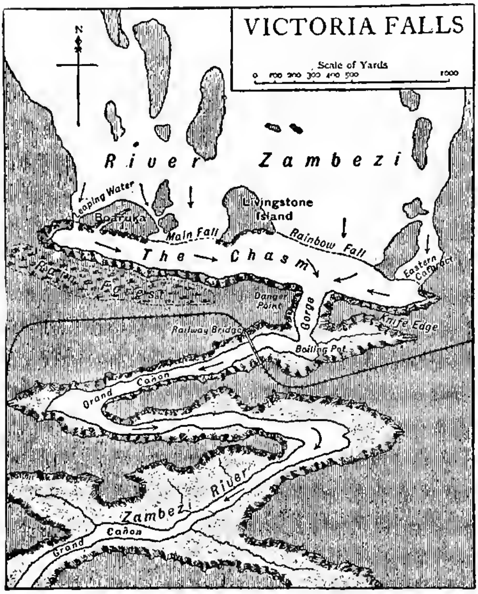


FIG. 77.—Map of the canyon below Victoria Falls. (After Encyclopædia Britannica.)

bezi River, in the second by the Snake River; and in each case there is an extensive gorge, or canyon, below the fall (Figs. 77, 78).

Falls in Dipping Rocks. — Difference in resistance of layers of rock that are inclined will give rise to falls or rapids as the water wears them away differently. But such falls differ materially from those in horizontal strata. Among the noteworthy differences is the manner of recession. The fall in horizontal strata recedes up-stream and may maintain or even increase its height as it recedes; but the fall developed in vertical strata, as it is worn away, loses height and recedes vertically. Between these extremes there is every gradation as the inclination

FIG. 78.—Victoria Falls, South Africa.

of beds varies. It follows, therefore, that a fall in inclined strata has a shorter life than one in horizontal strata.

Yellowstone Falls. — Of the falls due to vertical differences in rock resistance to river erosion the Lower Yellowstone Falls may be taken as a typical example. Here a vertical mass of more resistant lava crosses the weaker massive beds in which the great varicoloured canyon of the Yellowstone below the falls is excavated. The work of excavation is held back by the resistant layer and the water falls in a massive,

FIG. 79. — View down the canyon of the Yellowstone River from the brink of the lower falls. (Hillers, U. S. Geol. Survey.)

beautiful sheet into the canyon which it has excavated in the weaker lava. Gradually, however, the resistant layer will be cut away, and, as it is worn down, the crest of the fall will steadily sink (Fig. 79).

Law of Waterfall Formation. — The manner of development of a waterfall in a stream may be stated as a law, as follows: *when a stream, in seeking its grade, discovers sufficient difference in the resistance of the rocks in its bed, a waterfall (or rapid) will develop.* In both vertical and horizontal strata the fall will persist so long as the water, in excavating, discovers sufficient differences in resistance to cause an abrupt descent in the bed. When grade is reached, no matter what differences may exist in the rock of the river bed, no fall or rapid can exist.

Law of Waterfall Extinction. — The disappearance of waterfalls may therefore also be stated as a law, as follows: *when the stream grade intersects the fall producing layer, the waterfall will disappear.* Since the grade will intersect a vertical fall-producing layer directly beneath the point at which the fall started, much less cutting, and therefore much less time, will be required to cause its disappearance than in the case of a fall in horizontal strata which must retreat far up-stream before the grade intersects it.

Importance of Waterfalls

Advantages and Disadvantages to Man. — From one standpoint waterfalls are a disadvantage, from another an advantage, to man. Niagara illustrates both cases well. It is the greatest single obstacle to travel up and down the Great Lakes-St. Lawrence waterway, and to surmount it expensive canals have been constructed. On the other hand, the force of its falling water has come to be a source of enormous power for use in manufacturing, estimated as 4 million horse power. Formerly such power was of use only locally, but now it may be transformed to electric power and transmitted by wire far and wide. Thus Niagara power is used not only at Niagara Falls, but at Buffalo, and even in central New York.

Water Power. — The value of water power is illustrated in scores of manufacturing towns and cities in the United States, in New England, for example, and at Rochester, at Minneapolis, at Keokuk, Iowa, on the Mississippi, in the Fox River valley of Wisconsin, and many other places. Such power has been a factor of great significance in the industrial development of many nations; and now, by the aid of electric transmission, it seems about to enter upon a new and even greater usefulness.

Canals around Waterfalls. — As an obstacle to navigation, waterfalls are of importance only in the larger rivers, as at Minneapolis on the Mississippi, Louisville on the Ohio, the cataracts of the Nile, and the falls of the Kongo. When the demands of transportation are sufficient, the effect of the obstacle can be readily minimized by human effort, as the Canadians have done in their canal building around the rapids in the St. Lawrence, the English in railroad building along the Nile, and the people of the United States by canal at Louisville, by rail at Minneapolis, and by the same means in other places.

References to Literature

R. M. Brown. Bull. Amer. Geog. Soc., Vol. 34, 1902, pp. 371–383; *ibid.*, Vol. 35, 1903, pp. 8–16; *ibid.*, Vol. 39, 1907, pp. 147–158; *ibid.*, Vol. 44, 1912, pp. 645–657; *ibid.*, Vol. 45, 1913, pp. 500–509.

V. Cornish. Progressive Waves in Rivers, Geog. Journ., Vol. 29, 1907, pp. 23–31.

N. H. Darton. Bad Lands of South Dakota, Nat. Geog. Mag., Vol. 10, 1899, pp. 339–343.

A. P. Davis. The New Inland Sea, Nat. Geog. Mag., Vol. 18, 1907, pp. 37–49.

W. M. Davis. An Excursion to the Grand Canyon of the Colorado, Bull. Mus. Comp. Zoöl., Vol. 38, 1901, pp. 108–201; An Excursion to the Plateau Province of Utah and Arizona, *ibid.*, Vol. 42, 1903, pp. 1–50.

C. E. Dutton. The Physical Geology of the Grand Canyon District, 2d Ann. Rept., U. S. Geol. Survey, 1882, pp. 47–166; Monograph 2, U. S. Geol. Survey, 1882, 264 pp., and atlas.

H. C. Frankenfield, Bull. Y, U. S. Weather Bureau, 1913.

A. Geikie. Text-book of Geology, 4th edition, Vol. 1, 1903, p. 589.

G. S. Gibbs. The Breaking Up of the Yukon, Nat. Geog. Mag., Vol. 17, 1906, pp. 268–272.

G. K. Gilbert. Niagara Falls and their History, Nat. Geog. Monographs, New York, 1896, pp. 203–236; Rate of Recession of Niagara Falls, Bull, 306, U. S. Geol. Survey, 1907, 31 pp.

L. C. Glenn. Denudation and Erosion in the Southern Appalachian Region and the Monongahela Basin, Prof. Paper 72, U. S. Geol. Survey, 1911, 171 pp.

A. W. Grabau. Guide to the Geology and Paleontology of Niagara Falls and Vicinity, Bull. 45, N. Y. State Museum, 1901, 284 pp.

J. W. Gregory. Constructive Waterfalls, Scottish Geog. Mag., Vol. 27, 1911, pp. 537–546.

L. E. Hicks. Some Elements of Land Sculpture, Bull. Geol. Soc. Amer., Vol. 4, 1893, pp. 133–146.

W. G. Hoyt. Effects of Ice on Stream Flow, Water Supply Paper 337, U. S. Geol. Survey, 1913, 77 pp.

A. A. Humphreys and H. L. Abbott. Report upon the Physics and Hydraulics of the Mississippi River, Prof. Papers 4 and 13, Corps of Topographic Engineers, Philadelphia, 1861, and Washington, 1876.

D. W. Johnson. A Geological Excursion in the Grand Canyon District, Proc. Boston Soc. Nat. Hist., Vol. 34, 1909, pp. 135–161.

G. W. Lamplugh. The Gorge and Basin of the Zambezi below the Victoria Falls, Rhodesia, Geog. Journ., Vol. 31, 1908, pp. 133–152, 287–303.

H. G. Lyons. On the Nile Flood and its Variations, Geog. Journ., Vol. 26, 1905, pp. 249–272, 395–421.

W J McGee. Sheetflood Erosion, Bull. Geol. Soc. Amer., Vol. 8, 1897, pp. 87–112.

D. W. Mead. Notes on Hydrology, Chicago, 1904, 202 pp.

A. J. C. Molyneux. The Physical History of the Victoria Falls, Geog. Journ., Vol. 25, 1905, pp. 40–55.

C. C. O'Hara. The Badland Formations of the Black Hills Region, Bull. 9, South Dakota School of Mines, 1910, 152 pp.

J. W. Powell. Exploration of the Colorado River of the West, Washington, 1875, 291 pp.; Canyons of the Colorado, Meadville, Pa., 1895.

T. Mellard Reade. Addresses, Liverpool Geol. Society, 1876 and 1884.— See Geikie's Textbook of Geology, 4th edition, Vol. 1, 1903, p. 489.

I. C. Russell. Rivers of North America, New York, 1898, 327 pp.

N. S. Shaler. Aspects of the Earth, New York, 1900, pp. 143–196.

J. W. Spencer. The Falls of Niagara, Dept. of Mines, Canada, 1907, 482 pp.

R. S. Tarr. Physical Geography of New York State, Chapters V, VIII, IX, New York, 1902, pp. 155–192, 240–299; Prof. Paper 64, U. S. Geol. Survey, 1909, pp. 122–123.

F. B. Taylor. Origin of the Gorge of the Whirlpool Rapids at Niagara, Bull. Geol. Soc. Amer., Vol. 9, 1898, pp. 59–84; Folio 190, U. S. Geol. Survey, 1913.

Water Supply Papers. For floods, see U. S. Geol. Survey, Nos. 88, 1903; 96, 1904; 234, 1909; and 334, 1913; for volume and load of rivers in United States, see other Water Supply Papers, as in Nos. 44, 93, and 289.

G. M. Wheeler. Ascent of the Colorado River in 1871, Report upon U. S. Geog. Surveys, Eng. Dept., U. S. Army, Vol. 1, 1889, pp. 156–171.

TOPOGRAPHIC MAPS

Bad Lands

Rock Springs, Wyo.	Fort McKinney, Wyo.	Scotts Bluff, Neb.

Canyons

Bright Angel, Ariz.	Shinumo, Ariz.	Vishnu, Ariz.
Kaibab, Ariz.	Higbee, Colo.	Abajo, Utah.
Boise, Idaho.	Bisuka, Idaho.	

Immature Drainage

Glassboro, N.J.	Barnegat, N.J.	Norfolk Special, Va.

Waterfalls

Niagara Gorge, N.Y.	Quincy, Wash.	Great Falls, Mont.

Young Valleys

Fargo, N.D.	Marshall, Ark.	Hartford, Conn.

CHAPTER VI

RIVER DEPOSITS

River Bed Deposits

Stream Beds. — In the course of transportation of its sediment load t commonly happens that a river deposits a part of its burden in its)ed, though usually only temporarily and in spots. For this reason :ven the bed of a stream which is rapidly cutting a gorge will, if exposed o view, be found to consist not solely of bare rock, but in part of loose ock fragments which, for one reason or another, the stream had found t necessary to leave on its bed.

Deposits in Slowly-moving Water. — Among the various causes or such deposit the most important is change in velocity. A stream n flood may be sweeping along a quantity of sediment or rock fragnents of a size which cannot be moved when the flood subsides. As he velocity diminishes with the subsidence of the flood some of this oad must be left along the stream bed. As has been pointed out, a tream current is irregular, with some places of rapid flow, and others f quieter water; and the sediment which can be moved in the more apid stretches may come to rest in the quieter pools. Or a tributary tream with steep slope may bring fragments of a size which the nain stream cannot move onward. This finds excellent illustration in he Grand Canyon of the Colorado, where some of the tributary streams ave brought so many large fragments that the river is ponded back y them in lake-like expanses, while the current over the obstruction uickens to a violent rapid, — the greatest obstacle to navigation of he river by a small boat (Fig. 66).

Where streams flow through unconsolidated deposits of glacial drift, n which there are also large fragments of resistant rock, it is often he case that the smaller materials are removed, while the larger remain n the stream bed because they cannot be moved by the current. In uch cases the stream bed may become a mass of boulders, which, owever, the current is slowly wearing down.

Sand Bars. — River bed deposits of the kind described above are of o great importance, for they are of limited extent and very local as vell as temporary. But in streams that are heavily burdened, and specially in those that are so overburdened that they are aggrading heir beds, this class of deposit assumes considerable importance. n the Platte River, for example, sediment is steadily being deposited, and the bed is steadily rising. The deposit is not made in a uniform sheet, but more at some stages than at others, and more in some parts of the bed than at others. At one spot, where the current is slack, deposit may begin and a *sand bar* commence to develop, while on either side of it the current flows in a channel which its velocity is able to maintain. But as deposit proceeds the size and form of the sand bars change, and the channelways shift in position and vary both in size and in the volume of water. Therefore the river flows not in a single channel but in a multitude of *anastomosing* channels, which, together with the sand bars that separate them, are forever varying. Such a stream, split into many branching and reuniting channels, is called a *braided stream* (Fig. 80).

FIG. 80. — Braided stream courses in Alaska.

Obstacles to Navigation. — The formation of sand bars in a navigable stream is a menace to navigation, for their form and position are almost constantly changing. This is well illustrated in the lower courses of all large rivers, and is well described in Mark Twain's "Life on the Mississippi." Although not written as a treatise on geography, this gives an excellent word picture of the subject under consideration, as well as of other features of the navigable Mississippi. The stranding of a tree, or a slight variation in the current, may in a few hours cause a sand bar to develop where before there was navigable water. The heavy sediment load which the Mississippi bears and the consequent deposit which it is making offer the most serious obstacle to the utilization of this great waterway as a highway of commerce. The difficulty exists all the way from the river mouth to the mouth of the Missouri, which is the contributor of the bulk of its sediment load.

Floodplains

River Banks. — A river channel is bounded by banks, between which the river water commonly runs. Sometimes these are so steep and high and so near together that, as in some gorges, the river is always confined between them; but usually the banks that confine the river at ordinary stages of water are so low that at times of flood the water overflows them and spreads beyond them. Even in most gorges, as a result of lateral swinging, the gorge bottom is broader than the normal river channel, so that at times of flood the water spreads beyond the channel bank on one or both sides.

Deposits in Shallow Water. — During such an overflow the stream is apt to be most heavily sediment-laden; but, as the water spreads out beyond the banks, the current there is checked, because the stream is shallower than in the channel. Accordingly it may not be able to carry all the sediment which it bore before leaving the swifter channel portion. Then some must be deposited. The same process may be seen during a heavy rain, or the rapid melting of snow, when a swift stream in a gutter overflows the sidewalk and leaves a layer of sediment which its shallower current could not transport.

The Nature of Floodplains. — As a result of this process little strips of plain are built up even in a gorge, usually first on one side of the stream, then on the other side, as the stream swings away from the gorge wall, or, where the stream flows in the middle of the gorge, on both sides. Such a plain is a *floodplain*, for it is made by the floods; and it is a plain, because its surface cannot rise above the level to which the floods rise. In a gorge it may be a very rough, and a very small plain, and it may be made of coarse gravel.

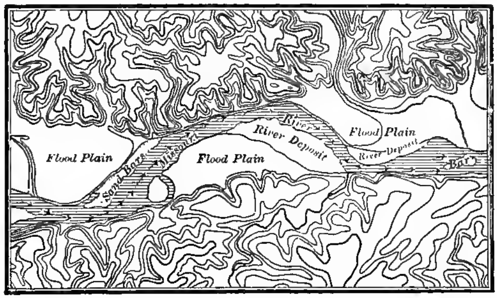


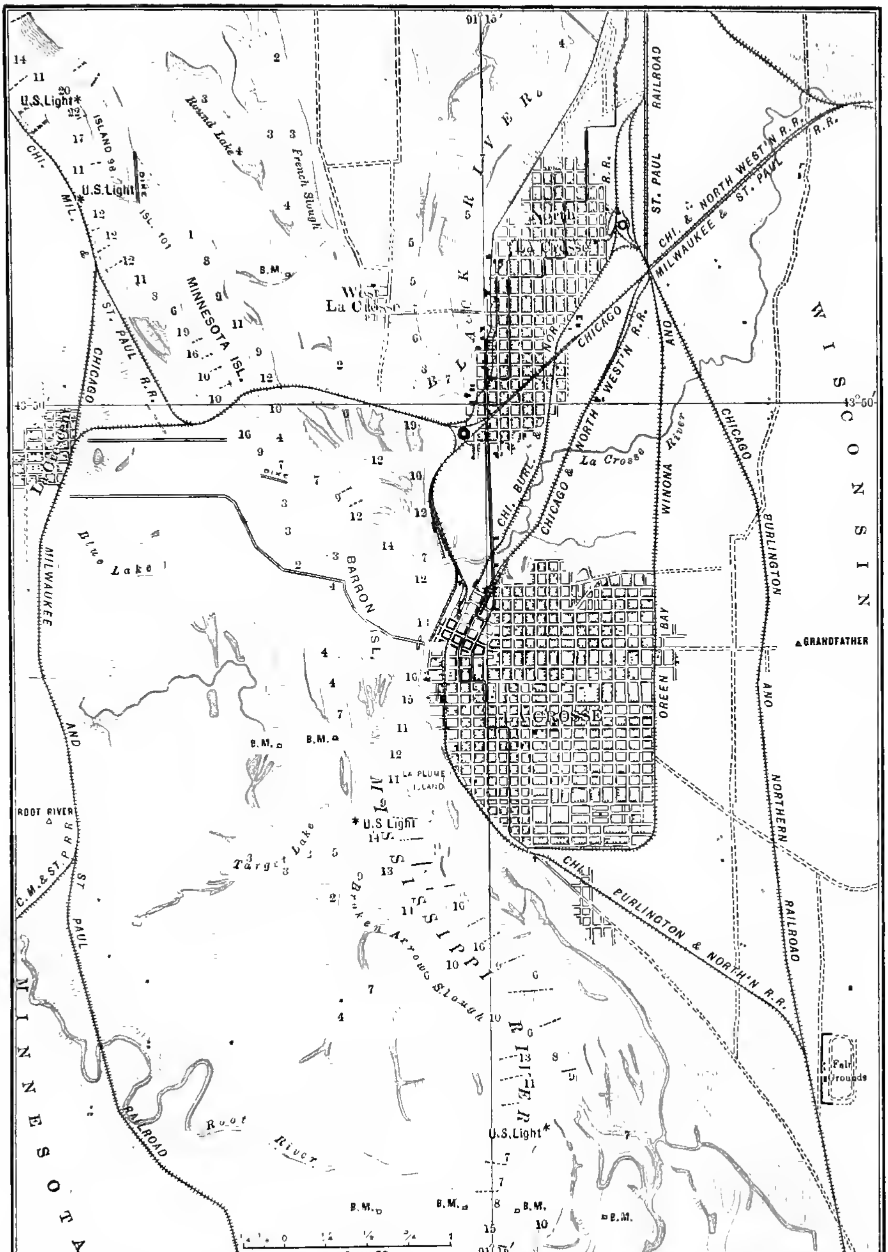
Fig. 81. — Floodplain of the Missouri River, showing where sand bar deposition is still adding to it.

Where streams flow in more open valleys and the valley walls are farther apart, the floodplain strips are wider; and if the slope of the stream be not too great, they are composed of fine gravel, or sand, or even of clay. But the most extensive floodplains are those that develop along streams which, for one reason or another, are aggrading their beds. Such a stream, like the lower Mississippi, at ordinary stage of water flows in a well-defined channel, bordered by low banks; but when floods come, and the channel can no longer hold the volume that is supplied, the water rises over the banks and spreads out in a sheet over the bordering lands. Here by the slackness of the current and by the interference with its motion caused by the vegetation, some of the sediment is of necessity deposited. Thus with each flood the level of the flooded land is raised, and gradually a plain is built on either side of the river. The sediment may accumulate to a depth of scores or even hundreds of feet, but all the time the form of the plain is maintained. Its extent is limited by the distance to which the floods can reach on either side of the river, and very often this is the wall of the valley which the stream is aggrading. In that case the floodplain terminates against the base of a bluff, or of a hillslope which is gradually being submerged by the rising floodplain (Fig. 81 and Pl. III).

Excessive Stream Load. — The condition under which floodplains develop is the presence of more sediment in time of flood than can be carried over the flooded lands. The majority of streams fulfil this condition, but to form extensive floodplains there must be frequent overflow and an abundance of sediment. The former depends upon variation in run-off, and is normal to most large streams in their lower course where the slope is so gentle that the channel is not competent to dispose of a great addition to the volume. The sediment is also normal to most large streams, for into some, if not all, of its tributaries there is almost certain to be a notable inwash of sediment with the run-off. For these reasons floodplains are typical phenomena of the lower courses of large streams.

Causes for Deposition. — The aggrading condition, under which the largest floodplains are developed, may result from several causes, as a result of which a river, after having excavated a valley, may proceed to aggrade it by floodplain deposit. One of the most common causes for the change from a condition of cutting to one of building up is the increase of the sediment supply. This may result from a change in rainfall conditions among some of the tributaries, on account of which the run-off sweeps along a larger burden of sediment, thus overburdening the lower, gently sloping course of the river. Or man, by stripping off the forest, may aid in giving the river a heavier burden of sediment than it can transport to the sea. But more common than either of these is the increase in surface from which sediment can be washed as the valleys of a river system are developed, cutting into land with a multitude of slopes down which sediment may be washed. Thus, floodplains are to be expected in the normal development of a valley system by the increase in sediment supply without a corresponding increase in run-off. If the sediment supply remains the same, while the rainfall diminishes, an overburdened condition may result, just as well as it may by increasing the sediment without a corresponding increase in the volume.

Effect of Change of Slope. — Another cause for an overburdened condition of a river that formerly was able to dispose of its sediment load, and even deepen its valley, is a change in slope. If a stream is graded to a certain volume of water and sediment, and then, by change in the level of the land, its slope is decreased, sediment deposit must



WILLIAMS ENGRAVING CO., N.Y.

MISSISSIPPI RIVER

The floodplain within the trench or gorge of the Mississippi at La Crosse, Wisconsin, with bayous and floodplain lakes. Contour interval, on the bottom land 5 feet, and on the bluffs 20 feet, with steep cliffs hachured. The disadvantage of two contour intervals in the same map is shown south of La Crosse where the bluff at the edge of the low terrace on which the city is located erroneously appears to be nearly as bigh as Grandfather Bluff. (From Charts 172 and 173, Mississippi River Commission, Engineer Corps, U.S. Army.)

take place. A similar result is reached by the building of a delta at a river mouth. For this disturbs the equilibrium of the stream by adding a level tract at its lower end, over which the water must flow with its sediment load. It cannot flow over a level surface, and must, therefore, grade up its bed so as to introduce a slope. This grading would pond back the waters of the river above the delta if it did not also extend up-stream. So, as a delta grows, a process of grading is introduced, not only on the delta, but far up-stream from it, for the river will undertake to adjust its grade to the new conditions. In this

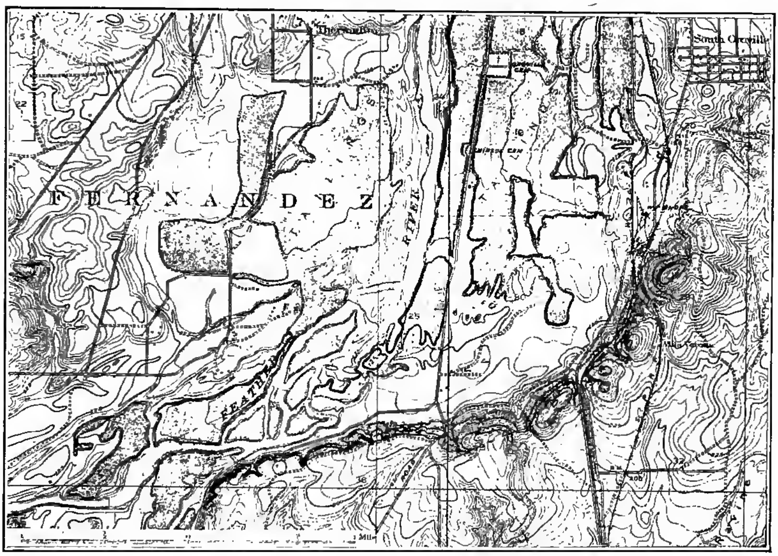


FIG. 82.—Map of floodplain deposits in California. Contour interval 5 feet. (Palermo Quadrangle, U. S. Geol. Survey.)

adjustment aggrading takes place, and with it an extension of floodplain development.

Deposits Greatest near River Mouths. — Floodplains are broadest and most extensive in the lower portions of large streams which have a heavy burden of sediment. Being in such situations, they are commonly made of fine-grained sediment, such as clay, since that is the size of particle which a current in that part of a large river can transport in suspension, for that which is dragged along the bed cannot be carried out on the floodplain in large quantities. Because of the levelness of the land, the fine texture of the soil, the fertility of the soil, the fertilizing of it by frequent overflow, and the dampness of the ground, large floodplains are favourable to agriculture, and many floodplains, especially in Asia, are the seat of a dense agricultural population.

Natural Levees. — The menace of the floods is a serious obstacle to successful occupation of such floodplains, though it is lessened to some extent by the presence of a low ridge on either side of the channel, called the *natural levee.* This levee may slope 5 to 10 feet per mile, as in the Mississippi, where it is 15 times as steep as the slope of the floodplain.

This levee serves as a partial protection against floods, and because of its height the soil is better drained than in the backwater swamp outside (Fig. 328). The natural levee of the lower Mississippi was early settled and is even now more fully occupied than the floodplain beyond. It was upon the natural levee that New Orleans was built, and both above and below this city the river is bordered on each side by a succession of plantations on the natural levee. How much of an embankment it is, may be seen by the fact that it prevents the entrance of some of the streams that flow toward the Mississippi, but take independent courses to the sea along the low floodplain beyond the natural levee. The Yazoo River is deflected for about 200 miles before it finally enters the Mississippi where the latter swings over against its valley wall at Vicksburg.

Cause of Natural Levees. — The cause for the natural levee is, first, the fact that coarser and more sediment can be deposited near the channel than on the more remote parts of the floodplain, and, secondly, that floods more often rise upon it. Only the greatest floods overspread the entire floodplain, whereas moderate floods are able to bring sediment to the natural levee.

Artificial Levees. — Upon the natural levee artificial embankments, or levees, are built to still further check the floods by confining the river in its channel. By such artificial levees large tracts of floodplain are rendered habitable that otherwise would be too frequently flooded for habitation. This is true in Holland, where dikes are built along the lower Rhine, and in Italy, where the Po is confined between the embankments, as well as along many other streams in both the new and old world.

River Meandering

River Courses. — On a large floodplain and on many small ones the river course is tortuous and even shifting. This is the result of lateral cutting, similar in character to that through which a stream broadens a gorge by lateral erosion. If a stream channel could be made perfectly straight with an absolutely perfect cross-section and be occupied by a current subject to no influence tending to divert it, the current would flow with greatest velocity along the middle and with least velocity along the banks. Such a channel might preserve a straight course. Manifestly, ideal conditions of this kind cannot exist in nature, for there are a number of ways in which streams normally depart from them. The stream channel is not straight; the cross-section is not

Fig. 83. — A meandering river in the Vale of Cashmere in India.

perfect, but, on the contrary, is very irregular as a result of deposit, or irregular erosion; and there is thought to be an ever-present tendency toward deflection from a straight course by the effect of the earth's rotation, through which moving bodies are deflected toward the right in the northern hemisphere and toward the left in the southern.

Lateral Erosion. — As a result of the actual conditions in the flowing water the current, instead of flowing with greatest velocity along the centre of the stream, is every here and there deflected from the centre toward the side. Lateral erosion, therefore, results. The effect of this lateral erosion becomes especially noticeable on large floodplains because (*a*) of the great volume, which gives the power for lateral cutting, (*b*) the slowness of the current, which makes deflection from the straight line more easy than in swiftly flowing water, and (*c*) the lowness and softness of the banks which enclose floodplain streams.

Cutting and Depositing. — If a stream with a straight course were established on a floodplain, deflection would at once commence. This deflection would consist of cutting at a certain point where the current was turned against the bank; but the cutting could not continue far if there was not corresponding deposit on the opposite side, for, without that, the breadth of the channel would be increased and the current, therefore, diminished. As a matter of fact, filling on one bank goes hand in hand with cutting on the other. This gives rise to a steep bank on the side of cutting and a gently-sloping sand or silt bank on the other, on which vegetation may not be able to encroach as fast as deposit builds it out into the river. On the side of deposit the water is shallow, on the side of cutting it is deep.

Cause of Meanders. — From the point of cutting the current is deflected, not abruptly, but along a curve, so that the cut face is a curve concave toward the river, while the built side is convex. Deflection from the curved face of cutting swings the current over against the opposite bank lower down, and there another curve of cutting, with opposed curve of filling, is begun. This process continues until the river swings over its floodplain in a great series of curves, or *meanders*, a term derived from the small river Meander in Asia Minor, which flows in meandering course over its floodplain and delta (Fig. 253).

Development of Meanders. — The perfection of the meander form depends upon the length of time during which a given curve or series of curves have been developing, the regularity of the deflecting force, and the uniformity of the floodplain deposits. In its most perfect form the meander is a horseshoe-shaped curve, or the curve of an oxbow. But for one reason or another this curve may not be reached, or may have been passed, so that there is, in reality, great variety in the form of a meandering river from one curve to another. The size of the curve is limited partly by the volume, partly by the slope of the river. A large-volume stream develops large meanders, but the same sized

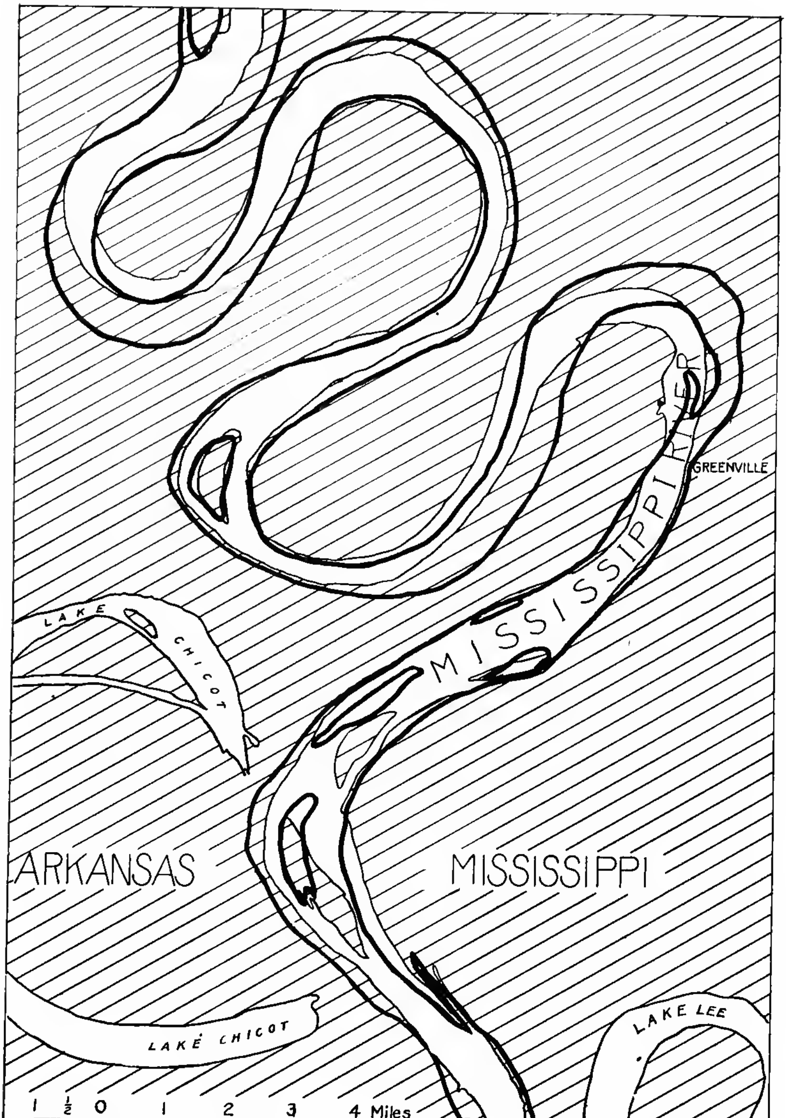


FIG. 84.—Shifting of meanders in the Mississippi from 1881 (light lines) to 1907 (heavy lines). Lakes Lee and Chicot are ox-bow lakes. (After Mississippi River Commission.)

stream would have even larger meanders with a gentler slope. On a small meadow brook a meander may be no more than 10 or 20 feet across, while some of the meanders of the lower Mississippi River are 6 miles across and 16 miles around their circumference.

Cut-offs. — The meander curve, in its normal development, while it grows outward to a certain limit on the cutting face, is constricted on the opposite side by the cutting action of the river. This constriction is caused by attack on two sides, on the upper side by the current deflected from the meander next above, on the lower side by the deflected current from the meander itself. With the growth of the meander this constriction becomes so reduced in width that finally the current breaks across the neck and the meander curve is abandoned, while the river flows temporarily along a straighter course at this point, giving rise to an *ox-bow cut-off*. When the ox-bow curve is abandoned its ends are sealed by deposit of sediment, and a circular lake, called an *ox-bow lake*, is formed in the floodplain. Slowly such a lake is filled by sediment as the river floods spread over the floodplain, and finally it is exterminated. On floodplains caused by meandering rivers all stages in the formation and extinction of ox-bow lakes are found (Figs. 84, 85). Some abandoned courses along the lower Mississippi are called *bayous*.

FIG. 85. — Ox-bow lake in the Connecticut valley in Massachusetts. As late as 1833 the Connecticut River still went around the meander.

Shifting of Meander Belts. — By its meandering a river may swing back and forth across its floodplain, thus temporarily laying aside sediment, later to pick it up again and move it a step down-stream. The extent of swinging is, however, not limited to the width of the meander, for the belt of meandering also shifts back and forth across the plain. Thus, while the larger meanders of the Mississippi are about six miles across, along the longest diameter, the area over which the river swings is several times that distance. In considering a meandering river, therefore, there is both the swinging of the river in the individual meanders, and the swinging first one way, then the other, of the meander belt.

Effects on Man. — Such constant shifting of a river course leads to constant change of great significance to those who dwell upon the floodplain of a meandering river. A farm may slowly be eaten away; the boundary of a state or of a county may be changed; and a town may be destroyed as the river cuts away its site, or it may be left far from the river on which it was built when the river swings away from it, or leaves it abruptly by taking a new course along a cut-off. The Mississippi and Missouri rivers have given numerous illustrations of the abandonment and destruction of towns and farms by the meandering river. So powerful and persistent is the action of a great meandering river that man is quite helpless in his efforts to confine it and prevent it from continuing its meandering.

River Towns and Meanders. — The meander belt of a floodplain is commonly bordered by a bluff, against which, from time to time, the river swings. This bluff is usually the old valley side, but it has been

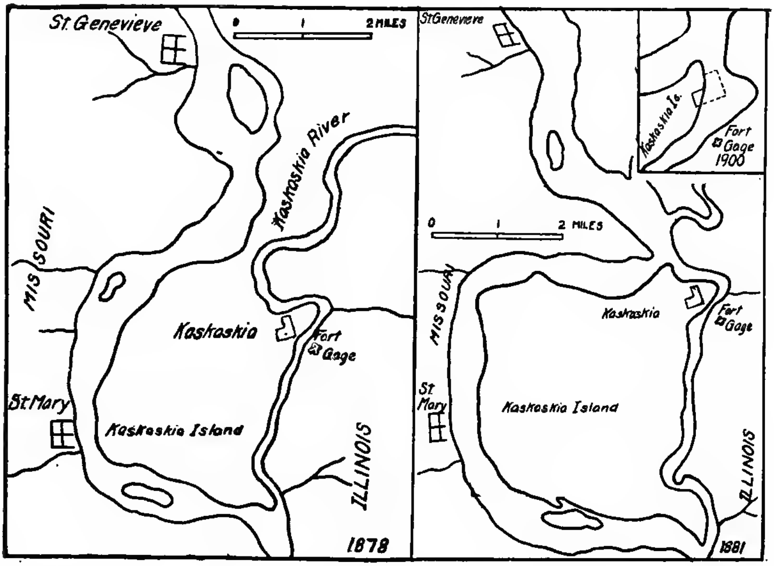


FIG. 86. — Three stages in meander development of the Mississippi River at Kaskaskia. (After Emerson.)

trimmed by the cutting of the river as the meander belt swings over to it. Upon such bluffs towns may be more safely built, as Vicksburg is on the Mississippi. But even these sites are unreliable, for a bluff town may be a river port to-day, and to-morrow the river may be several miles away. General Grant in his campaign against Vicksburg undertook to isolate that city by leading the river by an artificial cut-off across the neck of the meander that swings against the bluff there; but the river was not yet ready for the change, and the plan failed, although the stream cut off the neck of the meander about 13 years later, leaving Vicksburg on the bayou. The site of the town of Kaskaskia (Fig. 86), once the capital of Illinois, has been completely destroyed by a meandering stream.

Deltas

Deposits at River Mouths. — Some of the sediment that a stream transports finds its way ultimately to the mouth. If the stream is tributary to another, the master stream must dispose of the sediment, though sometimes the task is too great and a deposit is formed at and below the junction. If the stream terminates on the land, the sediment is necessarily deposited, thus giving rise to deposits whose characteristics are considered later. The other possibility is that the stream mouth is in a lake or in the ocean. In that case, the abrupt checking of the river current necessitates the deposit of the sediment, unless the water there is in sufficient motion to carry it away. This is not commonly the case, and therefore an accumulation of sediment is formed at the river mouth, often going to form a *delta* (Fig. 87).

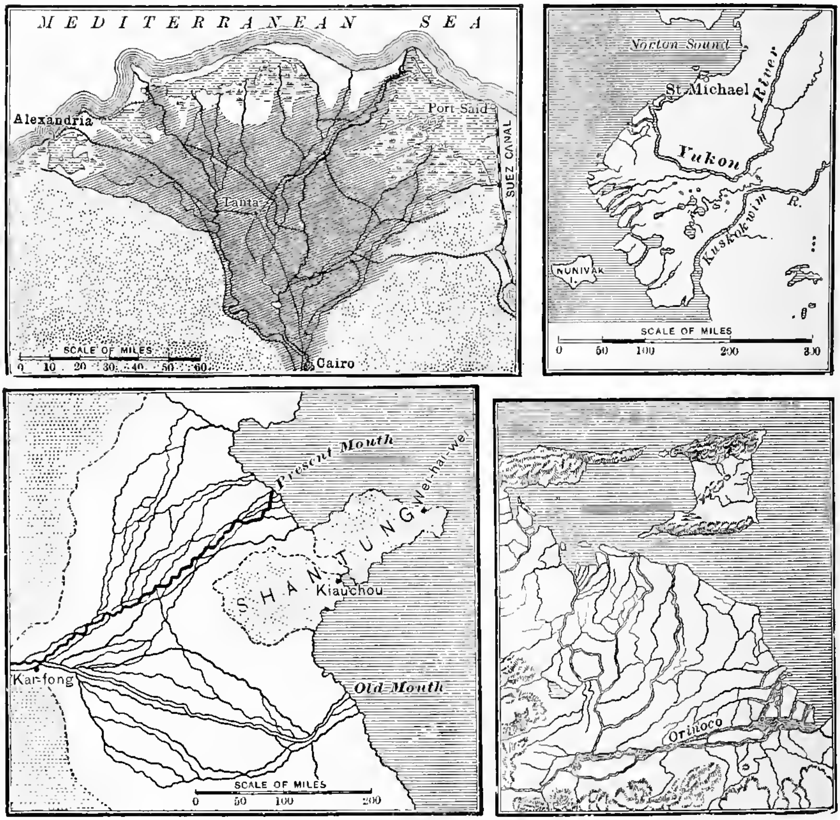


FIG. 87. — Various forms of deltas, the Nile, Yukon, Hoang Ho, and Orinoco.

Causes of Deltas. — While such deposits are found at the mouths of many rivers, they are by no means universal; they are, in fact, present at the mouths of only a small proportion of the rivers of the world. The conditions favouring delta formation are (1) a supply of sediment, (2) a checking of the current carrying the sediment so that it may settle, (3) sufficient stability of the sea bottom to permit the deposit to rise to the level of the sea, and (4) a sufficient length of time for the deposit to accumulate at the river mouth. The salinity of ocean water is said to also aid in deposition.

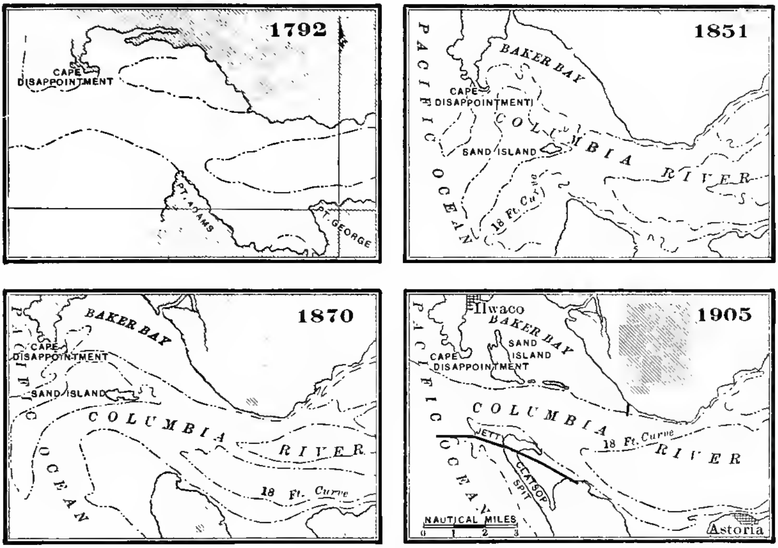


FIG. 88. — Four stages in accumulation at the mouth of Columbia River. (Putnam.)

Streams without Deltas. — It is because of the absence of some one of these conditions that deltas are not formed at the mouths of all rivers. Some streams carry so little sediment that a delta has not been formed at their mouths, especially in those cases where currents exist in the body of standing water, or where the river has not long entered it at the present point. Niagara River is an illustration of this condition, for it has little sediment and has only in a recent stage discharged into the lake at the present point. Many streams, especially those entering the open ocean, have their sediment distributed far and wide by the waves and currents. But an even more important cause for the absence of deltas is the recent subsidence of the land so that river mouths are submerged. A sinking sea bottom will soon lower a delta below sea level, and then even a moderate subsidence will suffice to exceed the rate of sediment accumulation. Many coasts, like those of northeastern America and northwestern Europe, have in recent geological time suffered subsidence, and, speaking generally, the streams of these coasts have not yet had time to build deltas in the new position of their mouths.

Effect of Quiet Water. — While deltas are not absent on open coasts, they are most numerous and more perfectly developed at the mouths of streams which enter lakes and enclosed or partially enclosed seas. This is not because such rivers have more sediment, nor can it be due, except in small degree, to the lesser depth and the greater stability of the bottom of such seas. The main reason is apparently the fact that in such seas the waves and currents are less effective in removal of sediment, and therefore the sediment load is concentrated in a deposit at the river mouth.

The Steep Delta Front. — Since the delta is due to the checking of the current which brings the sediment, its front lies beneath the sea

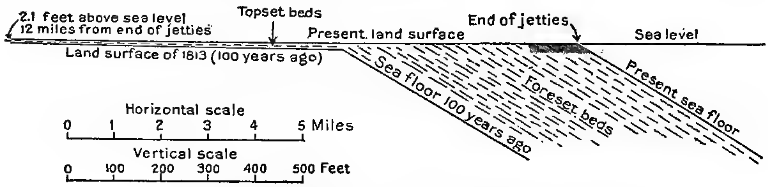


FIG. 89. — Cross section of Mississippi delta. (Shaw.)

at the point where the sediment can be carried no farther. This front is steeply sloping, and as the delta grows outward it advances, always maintaining its steep slope at the point where the abundant sediment settles. The layers that are deposited here have an inclination seaward, and they lie upon more nearly horizontal layers made of the finer sediment that had reached this part of the sea bed before the delta advanced over it.

The Flat Delta Surface. — Back of the steep front deposit continues until the delta surface is built up to sea level, and then it is raised higher still by the work of the waves which push back the sediment before them and throw some of it up in beaches or bars. Then, as the river rises in flood, it overflows the delta land and raises it higher still by floodplain deposit. Thus, nearly horizontal layers are deposited on the inclined delta layers as well as below them. The structure of a delta is illustrated in the diagram (Fig. 89). The form is that of a flat-topped plain at or above the level of the body of water in which it is built, and extending out beneath shoal water to a steep front, which abruptly descends to the level of the bottom of the lake or sea. The full form of the delta cannot ordinarily be seen, though it is known by soundings; and in some cases where lakes have formerly stood, perfect fossil deltas may be seen, with their typical steep fronts and flat tops. Artificial deltas, with all the characteristics described, may easily be made by causing running water to carry sediment from a sand pile into a small body of standing water; and perfect deltas of small size may often be seen, after a freshet, in the little roadside pools.

Relation to Floodplains. — The Nile illustrates typically the building of a delta. The sediment-laden water is checked by the Mediterranean, and the deposit is there building the land outward. As the plain is formed the slope of the river, both over the delta and above

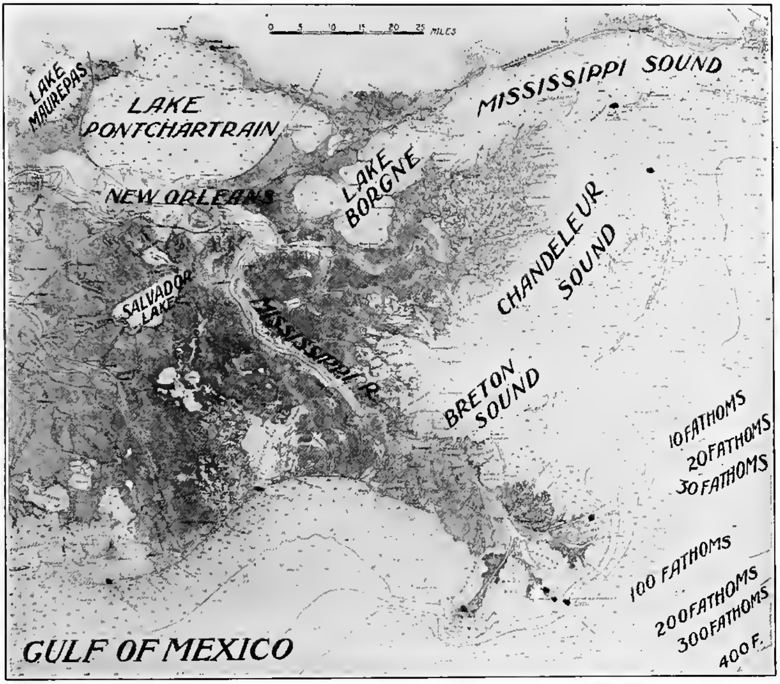


Fig. 90. — The Mississippi delta. (After U. S. Coast and Geodetic Survey.)

it, must be increased so as to permit the water to flow to the sea, otherwise it would be covered by a sheet of water, as it is when the volume is so increased during its annual floods that the river channels cannot carry it all. Therefore, both the river bed and the delta plain are raised, and the latter is transformed to habitable land, sloping toward the sea. Near the sea this new land is still swampy because not yet built up and given a slope by sediment deposit. As the delta is formed, the river above the delta must also correct its grade, as already stated, and during this aggradation floodplains develop. Indeed, the delta itself is ultimately transformed to a floodplain. One does not commonly think of the lower Mississippi from the mouth of the Ohio to the Gulf as a delta; yet this is what it is in fact, though graded up by floodplain deposit.

Distributaries. — Even with the grading that occurs on deltas, the delta plain of a large river is often so level that even the water of ordinary stages cannot find escape through a single channel. In consequence of this fact the river splits and flows over the level, lower

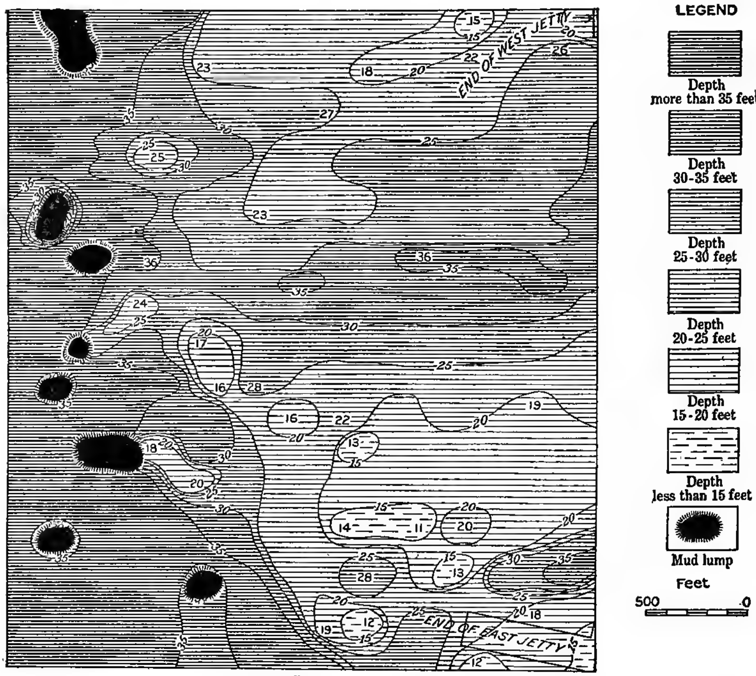


FIG. 91. — Map of one of the mouths of the Mississippi, showing location of mud-lumps. (After Shaw.)

portion in two or more channels, or *distributaries*, while in the time of flood the whole delta is inundated. It is common to consider the river delta as merely that portion below the point of splitting of the channel, and it was on this basis that the term delta originated from the resemblance of the Nile below Cairo to the Greek letter delta Δ.

Man may prevent deposition of sediment in distributaries by building jetties and quickening the current, so that the river scours rather than deposits. This was done on the Mississippi by the engineer, Eads.

All Deltas not Triangular. — There is much difference in the number and position of the distributaries of deltas, and there is much difference

FIG. 92. — The delta of the Danube.

also in the delta form and composition. When allowed to develop freely, a form approaching that of the Nile delta is common, both in large streams and in small. But where the growth is interfered with, there may be wide departure from that form. A delta, for instance, may be formed in a valley enclosed by mountain walls, and its lateral boundaries are therefore determined by it. This is illustrated in the delta of the Mekong River in Siam; and it is frequently illustrated in the deltas of inlet streams of lakes enclosed between valley walls, as at Ithaca, N.Y.

Mud-lump Development on Mississippi Delta. — It was pointed out nearly 50 years ago by Sir Charles Lyell, and later amplified by Hilgard, that the Mississippi delta is exceptional in its bird's foot terminus (Fig. 90). This is due to the rising of low *mud-lumps*, which have temporarily closed the mouths of several of the passes. The lumps (Fig. 91) are masses of tenacious, difficultly eroded clay. They are domed up at times of high water when sediment load of coarser clay is laid down faster than the creep of the finer and more fluid clay below can compensate for, or else where the seaward flow of semi-fluid clay is opposed by resistant foreset beds. Marsh gases escape from those mud-lumps, but the rise is not thought to be due to the gas. They form a serious obstacle to keeping the channels open, and to them is ascribed the peculiar form of the delta terminus.

Effect of Waves and Currents. — Another condition interfering with the perfect development of deltas is the effect of waves and currents. In Lake Cayuga, in central New York, the deltas are so modified by waves and currents that they are pointed on the outer end, and sometimes the points are turned away from the prevailing direction from which the waves come. The Rio Grande, which pours much sediment into the Gulf of Mexico, has succeeded merely in projecting the coast slightly as a rounded point; and much of its sediment load has found a resting place in the sand bars which sweep northward along the Texas coast. Great rivers are capable of building deltas against the waves, however, as in the case of the Mississippi. Even here the resistant sediment of the mud-lumps may affect the case, though in the Ganges-Brahmaputra delta the deposit is made in spite of strong tidal currents which aid the waves in carrying sediment away.

Steeply Sloping Deltas. — The delta surface slope also varies under different conditions. In large deltas, and even in small ones made of fine-textured sediment, the delta surface is a plain with almost imperceptible slope. But in deltas made of coarser sediment the slope must be graded up more steeply, otherwise the coarse fragments could not be carried across it. Some deltas in lakes between steeply rising mountain walls are made of large cobblestones and boulders, and the slope of such deltas must be steep. There is every gradation from deltas of such slope to those made of fine silt, in which the eye can detect no slope whatsoever.

Growth of Deltas. — The outward growth of deltas ordinarily proceeds at a fairly rapid rate. The Mississippi delta, for example, is normally advancing at the annual rate of 340 feet a year. The delta of a stream from Hidden Glacier in Alaska was built forward 1600 feet between 1899 and 1910, but this was a heavily loaded glacial stream.

Temporarily and locally, as between distributaries, delta growth may be exceedingly rapid. Thus the Mississippi delta advanced about 2000 feet in Garden Island Bay in the spring of 1912. What even the slow, normal growth of deltas means in the course of time may be inferred from the fact that Pisa, in the Middle Ages an important seaport, is now back from the sea on the Arno; the ruins of Ostia, the ancient seaport of Rome, lies three miles inland as a result of the outward growth of the delta of the Tiber, while Adria, a seaport at the head of the Adriatic 1800 years ago, is now fourteen miles inland; and scores of similar cases are known (Fig. 93).

Rapid as such deposit is, however, the total time required for the growth of a great delta is to be reckoned in many thousands of years. It is over 200 miles from the sea to the head of the Mississippi delta, and the total area is over 12,000 square miles, while the delta formed by the Ganges and Brahmaputra has an area of over 50,000 square miles. Since deltas may have a depth of several hundred feet, the vast amount of sediment that the rivers have poured into the sea is readily appreciated. The material represents rock fragments worn from the land surface. By its deposit at the river mouth, this sediment gives rise to the formation of new land built out of the waste of old land. The deltas are real additions to the land area, for the materials of which they are made have been obtained in the process of lowering of the land, not of its destruction.

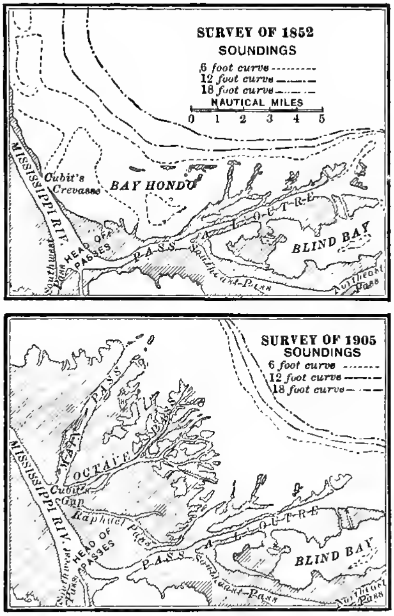


FIG. 93.— Growth of Mississippi delta at Cubit's Gap. (Putnam.)

Man's Use of Deltas. — As in the case of floodplains (p. 151) and other features of river valleys, deltas are much used by man, when the river has raised the delta enough so that it is not swampy. The deltas of the Ganges and Brahmaputra in northeastern India, of the Yangtse and Hoang Ho in eastern China, of the Po in Italy, the Nile in Egypt, and the Rhine in Holland and Belgium are among the most densely settled parts of the earth. The flat topography, the fertile soil, and the position where river valley meets the sea are responsible for this. Deltas in lakes are also often used as sites of towns, as at Interlaken, Switzerland, and towns on Lake Como (Fig. 94). Farms and towns are often found on deltas in the fiords of Norway and Alaska.

Floods on Deltas. — On the other hand, when there is a dense agricultural population on a delta, especial care is needed for protection against the floods. Those of the Nile come with such regularity that there is no danger from them; but the people of Holland have effectively shut out the Rhine and have even reclaimed a part of the delta which is beneath sea level. The delta of the Hoang Ho or Yellow River, on the contrary, though occupied for thousands of years by a dense agricultural population, is subject to such floods, of varying violence, that even the patience and labour of the Chinese have not sufficed to control it. Every now and then the river breaks through its embankments and rushes in a devastating flood over the densely settled neighbouring land. The river course has changed many times since records began to be kept by the Chinese over 4300 years ago, and some of these changes have shifted the position of the mouth several hundred miles. There have been 5 shifts from the Gulf of Pechili to the Yellow Sea and back, the river flowing into the former during 2 periods before the present, for a total of 3420 years and into the latter during 2 periods for a total of 792 years. A single flood, like that of 1887, has drowned a million people, besides destroying hundreds of villages, and causing famine by which the loss of life was greatly extended. It is no wonder that the Hoang Ho has been called "China's sorrow."

The vast destructiveness of the Hoang Ho is due in large part to the effort to confine a river which is aggrading its bed. The result of this is that the river bed is built higher and higher, and the surface of the water becomes higher than the surrounding land, as the Po has come to be in Italy. If then a part of the embankment gives way, or if a great flood rises above the embankment, the water naturally sweeps over the lower land from which it has been excluded. Similar, though less disastrous, floods occur along other rivers on deltas.

Deposits on the Bed of the Sea

Sediment Carried beyond Deltas. — Rivers also carry to the sea sediment which does not come to rest in deltas. Some of this is drifted away from the coast by currents and settles to the sea floor. Some of it is driven along the coast and built into beaches and bars. Some settles in bays and other indentations along the coast. Thus sedimentary strata are being formed on the sea floor out of sediment derived in part from the waste of the land by river action. Added to these deposits are the remains of marine organisms. The shells or other hard parts of these organisms are composed of mineral substances which were dissolved by underground water, transported to the sea by the rivers, and then extracted from the sea water by plants and animals and, upon their death, contributed to the sediments accumulating on the sea floor.

These sedimentary strata may, by uplift, be transformed to dry

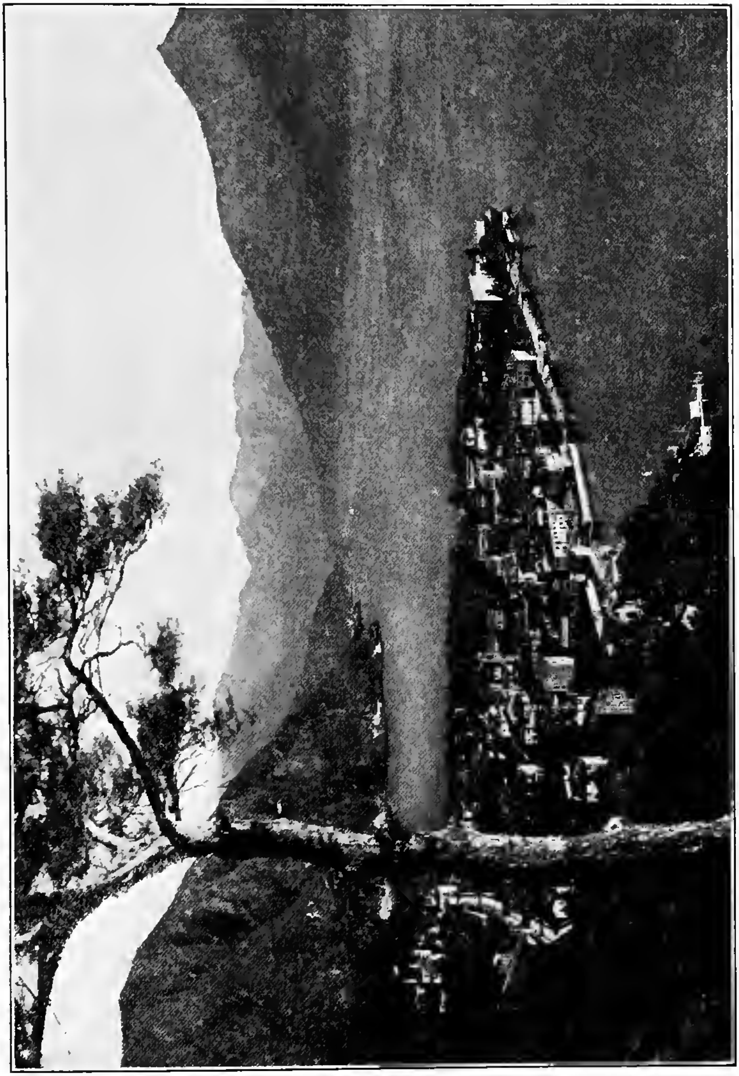


Fig. 94. — The city of Menaggio on a delta in Lake Como in the Italian Alps.

land, and this has been the origin of much of the rock of the continents. This subject will be followed no further at present than to point out that this is one important phase of river work in the process of developing the physical features of the earth's surface.

Alluvial Fans

Deposition through Change of Slope. — When the bed of a stream decreases in slope, the velocity of the stream is lessened, and, therefore, its transporting power is decreased. Such a change in slope is common where streams descend from mountains to plains or plateaus, and also

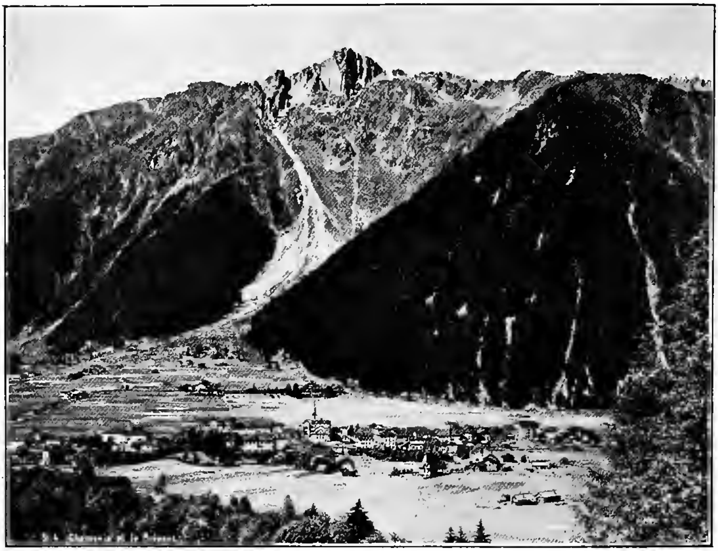


Fig. 95. — Alluvial fan in the Alps.

where tributary streams descend from steeper courses into a valley of moderate slope. At such points it frequently happens that the stream can no longer transport its sediment load, but is forced to deposit some of it. Such a deposit, called an *alluvial fan*, spreads out, fan-shaped, at the point where the stream emerges from its steeper portion. It is fan-shaped because it is being aggraded, and when one part is built up, the stream shifts to another course and grades that up. Thus, in time, the entire surface is reached by the shifting stream. In many cases the fan-building stream splits into a series of distributaries and then several beds are being aggraded at the same time; and, during periods of flood, numerous distributaries may develop.

Variations in Size. — The size of the alluvial fan varies greatly, from little deposits but a few square inches or square feet in area, where rain-born rills descend a steep clay bank, up to extensive fans of large streams, which may have a radius of thirty or forty miles. They vary in depth, too, some reaching a depth of several hundred feet near their apexes.

Variations in Material. — Ordinarily alluvial fans are made of coarse material such as sand and gravel, since they are made by the deposit of sediment brought by rapid streams; but they may be composed of fine silt, especially at their peripheries.

According to the coarseness of the sediment and to the volume of water, there is much variation in the surface slope of the alluvial fans. Those made of fine sediment are flatter than those of coarse rock fragments, and those made by small streams are steeper than those built by large streams. On some large alluvial fans there is an almost imperceptible slope, while others are quite steep. There is, in fact, every gradation from alluvial fans to the cone-shaped deposits at the base of cliffs where running water adds to the talus deposits enough material to cause a *cone of dejection* to rise above the talus toward some point in the cliff face.

Distinction from Deltas. — Some of the steeper alluvial fans may be called *cone deltas*, and this name is, in fact, sometimes applied to alluvial fans as a whole. They are, however, neither true cones nor deltas. Yet there is a certain semblance to deltas, and enough perhaps to class them as deltas on the land. Like deltas they are due to deposit of sediment through a decrease in carrying power of the water; they have the general delta form; they are areas of aggradation; and they are crossed by distributaries. They differ from deltas in place of accumulation, and in the uniform frontal slope in place of the steep, submerged delta front. Many small deltas of steep slope, like those in lakes among mountains, closely simulate alluvial fans in the part above water, and these parts are sometimes called alluvial fans. In a sense they are alluvial fans built up on deltas.

Decrease in Volume of Streams on Fans. — One factor in the growth of alluvial fans is the decrease in water supply for transporting the sediment. For, once a fan is started, a porous bed is provided, into which the water readily sinks. On many such fans no stream appears except at flood stage, for the water sinks into the gravel at or near the apex, and if it reappears at all, comes out in one or more springs at the periphery of the fan. Manifestly, such complete loss of water necessitates complete abandonment of sediment load; and from this extreme there is every gradation to those in which only a part of the water finds its way across the alluvial fan during ordinary stages. At all times there is a notable loss of water by seepage into the alluvial fan, and consequently a loss in transporting power. Added to this is the diminution in velocity induced by shifting of the stream into two or more smaller distributaries (Fig. 96).

Large Fans in Arid Lands. — Alluvial fans occur in all climates, but they are best developed in arid and desert regions, where they sometimes assume great size. In such countries stream after stream builds a fan on emergence from a steeper course, and the mountain bases are fringed with a succession of fan-shaped alluvial plains sloping away from the mountain, forming a looping fringe of evenly graded surface over which stream channels extend, and the size of which is roughly proportional to the size of the streams which built it. Very often these alluvial fans coalesce, or they may completely cross a valley and unite with those from the opposite valley slope. Such fan deposits, in all variety of size and slope, form a characteristic feature of arid land topography, carrying graded slopes of unconsolidated sediment up to and even up on the mountain slopes (Fig. 97).

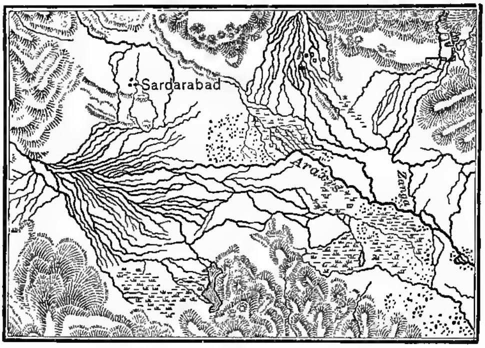


FIG. 96. — Alluvial fans in Armenia.

There are apparently three prime reasons why alluvial fans attain the height of development in arid regions: (1) the nature of the rainfall, which is intermittent, and, when it comes, is often violent enough to cause rapid run-off; (2) the bare slopes, which, having little vegetation, permit a rapid run-off and an abundant sediment supply to the streams to which the occasional rains give rise; (3) the rapid evaporation, as a result of which the volume of the fan-building stream is diminished, thus adding another factor to its inefficiency, in addition to change of slope and loss of water through seepage.

Uses by Man. — The evenly graded surfaces of large alluvial fans are frequently excellent farm land; and in arid regions they are very often irrigated. Many oases in the deserts are irrigated alluvial fans, forming garden spots in the midst of the desert. Irrigation is favoured in such situations, first, by the fact that there is often a steady supply of water at the apex of the fan, and, secondly, because the grade of the fan is favourable for the construction of the irrigation canals.

In the valleys of humid regions small alluvial fans of tributary streams are often chosen as town or village sites, because they are above the valley bottom and therefore offer drier sites. Such towns are, however, menaced by the danger of the shifting of the stream course and by the destructiveness of the torrents that sometimes flow over the fans. In Switzerland, and elsewhere, the alluvial fan streams are straightened and transformed to canals where they flow through the towns; but even with such careful regulation they are often the cause of much damage.

Desert Valley Filling

The Sources of Valley Filling. — The growth of alluvial fans and the less definite forms of deposit caused by the rain wash are sources of valley filling. The effect of these processes may be seen even in humid regions, where alluvial fans are common in the valleys of hilly and mountainous sections, and where the hill base is often fringed by

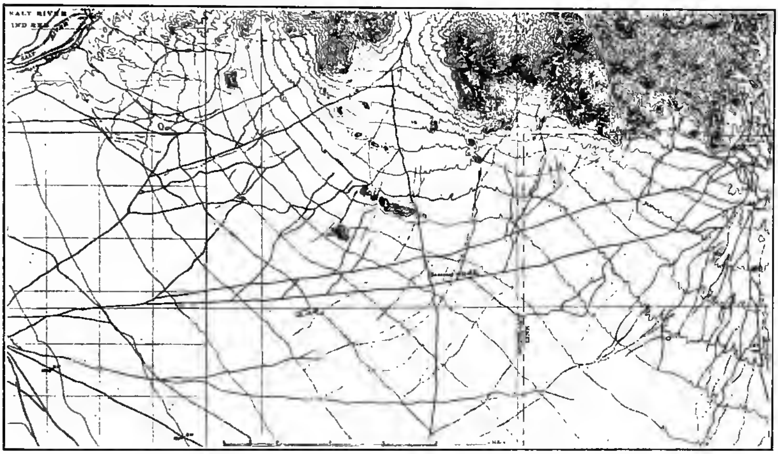


FIG. 97. — Coalescing alluvial fans in central Arizona. Contour interval 50 feet. (Desert Well Quadrangle, U. S. Geol. Survey.)

a deposit of rain-washed sediment, even when no definite stream descends to the valley.

Filling of Arid Valleys. — In arid countries, and especially in deserts, the influence of such deposits upon the topography is much more clearly seen, for there the rainfall is ordinarily so slight that the streams are unable to move out of the valleys all that is brought into them by the tributary streams and the rain wash. Consequently a portion, and often a very large portion, of the sediment derived from the waste of the bordering hills or mountains finds a resting place in the valleys, with the result that they are slowly filled by the inwash of sediment.

Basins without Outlets. — Naturally, in interior basins, out of which no water flows, all the sediment that finds its way in remains there, excepting that portion that is transported out of the basin by the wind. Thus the valleys of interior basins are often deeply filled with such sediment. In such arid lands, however, a part of the deposit, and a considerable part of its final arrangement of it, is caused by the action of the wind.

Description of an Arid Valley. — The great valley of California, especially in its more arid southern portion, illustrates this desert valley filling, as do also the smaller intermontane valleys of southern California, Arizona, and Nevada. In such a valley the enclosing walls are angular mountain slopes, showing evidence of the operation of arid land denudation, and transected here and there by valleys leading back into the mountains. At the mouth of each of these valleys is an alluvial fan, whose size is roughly proportional to the size of the mountain valley which it terminates, and whose slope is roughly proportional to the slope of the valley down which the sediment has been brought. Near the mountain base the alluvial fans have their steepest slope and their coarsest sediment, perhaps even in large part boulders and large cobblestones. Between the fans is an alluvial slope rising up on the mountain base, or, if the mountain is precipitous, a talus. In any event, the valley bottom rises toward the mountains with a slope increasing as the mountain base is neared; and this rise, due to deposit of rock waste, contrasts strikingly with the more ragged outline of the mountain.

Away from the mountain the slope of the alluvial fans and other deposits decreases, and if the valley is broad, becomes almost imperceptible. At the same time the sediment decreases in coarseness. If the climate is very arid, wind work begins to manifest itself here, and areas of dunes may be present, or, if not, the evidence of wind action is readily seen in the tufts of vegetation that grow upon the sand mounds. Over the flatter portion of the valley bottom wind work is apparently more effective as a distributor of sediment than running water.

Such deposits may accumulate to depths of many hundreds of feet. The slopes leading away from the mountain walls may be of unequal extent on the two sides, as they are in the southern part of the great valley of California, where the streams from the east, coming from the Sierra Nevada, are much larger than those coming from the lower Coast Ranges on the west. The drainage of the main valley is along the axis between the fans of the two sets of streams; and, by the growth of these fans, the feeble drainage may even be ponded to form a lake or a marshy tract, as in Tulare Lake formed by the alluvial fan of King River.

River Terraces

The Nature of Terraces. — If, for any reason, a valley that has been partly filled by sediment is excavated again, the alluvial filling is, during the process, carved into a series of *terraces* with flat top and steep face. These may rise one above the other, and occur on both sides of the stream, sometimes in long parallel strips, but more commonly in strips of variable length and width as well as at different levels. Two terraces, each ten or fifteen feet high, may merge into a single one, twenty or thirty feet high, or a single terrace strip may split into two or three terraces either up or down stream.

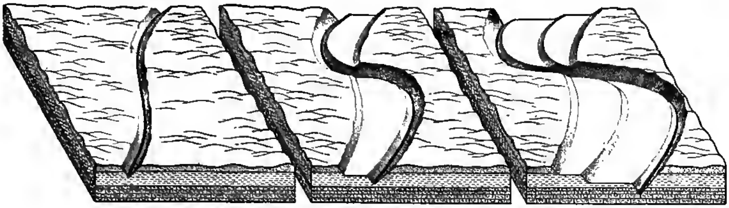


FIG. 98. — Three stages in the making of terraces.

Terrace Cutting. — Such terraces are the remnants left in the as-yet-incomplete removal of the valley filling. As the stream is cutting down in the alluvium, it meanders, as all streams tend to do. Cutting laterally for a while at one side of the valley filling, it excavates the alluvium, giving it a steep face toward the stream. If, then, the stream swings away from this bank to the other side, it scours out a level floor as it swings. Then, standing for a while at this new position, and cutting down into the bed, it makes a new terrace face. Thus as it swings back and forth, but cutting into the valley filling all the time, a succession of terraces is produced (Fig. 98).

Terrace Preservation. — Ultimately all of the filling would be removed, and the terraces are to be considered as uncut remnants, representing stages in the removal. By this process alone terraces may be formed, but many, if not most, terraces depend upon still another factor, namely, unequal resistance to the lateral swinging of the terrace-making stream. The presence of massive resistant deposits in the valley filling or of boulders may check the lateral swing of the river; but, more important still, if the swinging stream discovers rock spurs buried beneath the fill, there is an effective cause for the checking of the lateral erosion. Such spurs are not uncommon in valleys filled with alluvium. By checking the lateral swinging of the river such rock spurs act as a defence for those terraces below that were formed at an earlier stage before the discovery of the rock defence, and also for the terrace being formed while the stream is swinging against the rock spur. Such terraces have been called *rock-defended terraces*, and they are found

FIG. 99. — Terraces in a valley of the Andes in Peru.

to be common. Were it not for such defence the swinging stream would prove much more destructive of terraces previously formed, and the terraces would be much less numerous, extensive, and perfect.

Cause for Terracing. — That a stream should find power to excavate a filling previously made in its valley is not difficult to explain. A river, aggrading its valley under a certain condition of rainfall, may, if the rainfall increases, commence removing the filling. Such climatic change is known to have occurred in past times.

Or if an aggrading river suffers a diminution in its sediment load, it may be able to excavate deposits previously laid down. Such a change is not uncommon; as, for instance, the change from streams heavily loaded with sediment that issued from the front of the continental glacier during the Glacial Period, and flowed down a valley now occupied by streams with a much smaller burden of sediment. Many of the terraced river valleys have been formed by the excavation of deposits resulting from glacial action of one kind or another. Even without change, either in rainfall or in sediment load, a river may excavate valley filling if its slope is increased by uplift of the land.

Finally, a lake, acting as a temporary baselevel to a stream, may be filled, and then, the stream having a new and lower baselevel, it may proceed to remove the deposit that it laid down in the lake. It is under one or the other of these conditions that the excavating of valley alluvium, with accompanying terrace formation, may succeed a period of valley filling.

References to Literature

J. Barrell. Relation between Climate and Terrestrial Deposits, Journ. Geol., Vol. 16, 1908, pp. 159–190, 255–295, 363–384; Criteria for the Recognition of Ancient Delta Deposits, Bull. Geol. Soc. Amer., Vol. 23, 1912, pp. 337–446.

R. M. Brown. The Protection of the Alluvial Basin of the Mississippi, Pop. Sci. Monthly, Vol. 69, 1906, pp. 248–256.

J. E. Carmen. The Mississippi Valley between Savanna and Davenport, Bull. 13, Illinois Geol. Survey, 1909, 96 pp.

L. J. Cole. The Delta of the St. Clair River, Geol. Survey of Mich., Vol. 9, Part 1, 1903, 28 pp.

H. Credner. Die Delten, Petermanns Geog. Mitteilungen, Ergänzungsheft 56, 1878, 74 pp.

W. M. Davis. The Fresh-water Tertiary Formations of the Rocky Mountain Region, Proc. Amer. Acad. Arts & Sci., Vol. 35, 1900, pp. 345–373; Development of River Meanders, Geol. Mag., Decade 4, Vol. 10, 1903, pp. 145–148; River Terraces in New England, Geographical Essays, Boston, 1909, pp. 514–586.

R. E. Dodge. The Geographical Development of Alluvial River Terraces, Proc. Bost. Soc. Nat. Hist., Vol. 26, 1894, pp. 257–273.

F. V. Emerson. The Geographic Story of Kaskaskia, Journ. Geog., Vol. 8, 1910, pp. 193–201; Life along a Graded River, Bull. Amer. Geog. Soc., Vol. 44, 1912, pp. 674–681, 761–768.

E. F. Fisher. Terraces of the West River, Proc. Bost. Soc. Nat. Hist., Vol. 33, 1906, pp. 9–42.
G. K. Gilbert. The Transportation of Débris by Running Water, Prof. Paper 86, U. S. Geol. Survey (in press).
A. W. Grabau. Early Paleozoic Delta Deposits of North America, Bull. Geol. Soc. Amer., Vol. 24, 1913, pp. 399–528.
E. W. Hilgard. The Exceptional Nature and Genesis of the Mississippi Delta, Science, N. S., Vol. 24, 1906, pp. 861–866; Amer. Journ. Sci., 3d series, Vol. 1, 1871, pp. 238–246, 356–368, 425–435.
M. S. Jefferson. Limiting Width of Meander Belts, Nat. Geog. Mag., Vol. 13, 1902, pp. 373–384.
L. C. Johnson. The Nita Crevasse, Bull. Geol. Soc. Amer., Vol. 2, 1891, pp. 20–25.
Sir Charles Lyell. Mud-lumps off the Mouths of the (Mississippi) River, Principles of Geology, Vol. 1, 1867, pp. 447–454.
D. T. McDougal. The Delta of the Rio Colorado, Bull. Amer. Geog. Soc., Vol. 38, 1906, pp. 1–16.
Lawrence Martin. The Copper River Delta, Alaskan Glacier Studies, Washington, 1914, pp. 458–466.
J. Menauer. Die Laufänderungen des Gelbes Flusses in Historischen Zeit, Nurnberg, 1912.
A. Norlind. Die Geographische Entwicklung des Rheindeltas bis um das Jahr 1500, Lund, 1912, 272 pp.
E. W. Shaw. The Mud Lumps at the Mouths of the Mississippi, Prof. Paper 85B, U. S. Geol. Survey, 1913, pp. 11–27.
A. L. Smith. Delta Experiments, Bull. Amer. Geog. Soc., Vol. 41, 1909, pp. 729–742.
R. S. Tarr and O. D. von Engeln. Representation of Land Forms in the Physiography Laboratory, Journ. Geog., Vol. 7, 1908, pp. 73–85.
W. S. Tower. The Development of Cut-off Meanders, Bull. Amer. Geog. Soc., Vol. 36, 1904, pp. 589–599.
A. C. Trowbridge. The Terrestrial Deposits of Owens Valley, California, Journ. Geol., Vol. 19, 1911, pp. 706–747.
B. Willis. Conditions of Sedimentary Deposition, Journ. Geol., Vol. 1, 1893, pp. 476–520.

TOPOGRAPHIC MAPS

Alluvial Fans

Desert Well, Ariz.	Amargosa, Cal.	Livingston, Mont.
Needles Special, Ariz.	Cucamonga, Cal.	Sierraville, Cal.
Camelsback, Ariz.	Parker, Ariz.	

Bluffs

Jefferson City, Mo.	Lexington, Neb.	Elk Pt., S.D.

Braided Courses

Gothenburg, Neb.	Lexington, Neb.	Disaster, Nev.
Maxwell, Cal.	North Platte, Neb.	Kearney, Neb.

Deltas and Distributaries

East Delta, La.	West Delta, La.	Plattsburg, N.Y.
Cucamonga, Cal.	Donaldsonville, La.	

Floodplains

Map of Alluvial Valley of the Mississippi, 8 sheets.
Mississippi River Commission, 1 : 63,360. Charts 14, 16, etc.,
Mississippi River Commission, 1 : 20,000. Charts 8, 22, 35, 36, 38, 39, 52, etc.
Missouri River Commission, 1 : 63,360, Sheets I, LXXI, LXIV; also Sheets XIV and XXIII, editions of 1878–1879 and 1890, compared for floodplain and river changes at Kansas City and Omaha. For latter see also U. S. Geol. Survey map of Omaha and vicinity, 1 : 62,500, 1898 edition.
Map of Salinas Valley, Cal., 1 : 31,680, Sheets 1 to 3.
Map of Sacramento Valley, Cal., 1 : 31,680, Sheets A to Q.

Kearney, Neb.	Nebraska City, Neb.	Minneapolis, Minn.
Butler, Mo.	Donaldsonville, La.	Marshall, Ark.
Lacon, Ill.	Ottawa, Ill.	Isleton, Cal.
St. Louis, Mo.	Jefferson City, Mo.	Palermo, Cal.
Lake Providence, La.	Browns Valley, Cal.	Nocalaus, Cal.
Jonestown, Miss.	Bouldin, Cal.	Chico Landing, Cal.

Meanders

Millikin, La.	Butler, Mo.	Jefferson City, Mo.
Elk Pt., S.D.	Junction City, Kan.	Coahoma, Miss.
Fort Payne, Ala.	Estillville, Ky.	Marshall, Mo.
Maynardville, Tenn.	St. Louis, Mo.	Ypsilanti, Mich.

Natural Levees and Crevasses

Donaldsonville, La.	East Delta, La.	Maxwell, Cal.

River-made Plains and Graded Rivers

Shasta, Cal.	Amargosa, Cal.	Marshall, Mo.
Marysville, Cal.	Maxwell, Cal.	Elk Pt., S.D.

Terraces

Cohoes, N.Y.	Springfield, Mass.	Lacon, Ill.

CHAPTER VII

THE RIVER VALLEY CYCLE

Davis's Scheme of the Cycle

One of the great contributions to physiography is the statement, exposition, and persistent teaching, by Professor W. M. Davis, of the idea that land forms pass through a cycle of development. This has not only led to a clearer understanding of the physiographic processes, but has been a powerful factor in the rational interpretation of the physiographic features of the lands. While applicable to other land forms, this idea is of most fundamental importance in an interpretation of river valleys. The *geographical cycle* has been defined as "the period of time during which an uplifted land mass undergoes its transformations by the processes of land sculpture, ending in a low featureless plain."

The Earliest Stage of Youth

An Uplifted Sea Bottom. — For the statement of the cycle of development of river valleys, the clearest exposition can be made by considering first the simplest case, and at appropriate points indicating the variations from this. For this purpose we will assume a new land surface, elevated from the sea to no great height, sloping toward the sea, and in this finished state subjected to rainfall. This is no purely ideal case, but one that, with unimportant variations, has occurred repeatedly during the earth's history.

Effect of Slopes. — The rain that falls on this new land surface will run down the slopes toward the sea, and, where there is slope enough, will quickly find some parts lower than others toward which the run-off tends to concentrate. Along these lines there is excavation, and with excavation still greater tendency for the water to concentrate there from the neighbouring higher portions. And as the water flows toward these channels, tributary channels are cut.

Consequent Streams. — Elsewhere the surface may be too level for run-off, and there swampy tracts are developed by the standing water. Portions of the plain may contain original depressions where ponds or lakes accumulate. On such youthful flat divides water is removed chiefly by evaporation.

The course of any particular channel is determined by the natural irregularities of the surface, and it may assume a very sinuous route to the sea, passing through swamps, through lakes, around low elevations, and even falling in a rapid or low waterfall as it descends some unusually steep slope. This course is consequent upon the natural features of the surface, and the stream may be called a *consequent* stream, as the falls are also consequent (Fig. 100).

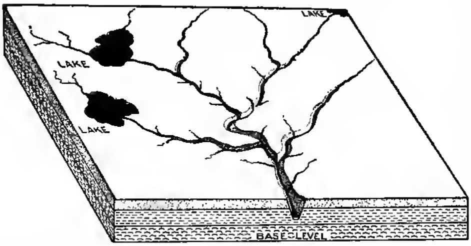


FIG. 100. — Youthful drainage with lakes, few tributaries, flat-topped divides, and the stream high above baselevel.

Illustrations from Florida and Dakota. — A near approach to this ideal condition is found in the southern part of the Florida peninsula, a recently uplifted sea bottom, with consequent drainage of exceedingly immature type. A recently drained lake bed, like that in the valley of the Red River of the North, in North Dakota and Manitoba, gives rise to a similar condition of immature drainage. Coastal

FIG. 101. — A young stream in Florida.

plains and former lake beds in many other parts of the world have a drainage in this or in only a slightly more advanced stage of development.

YOUNG VALLEYS

Earliest Cutting near Stream Mouths. — As the run-off from the new land proceeds, the channelways are deepened. Each main stream that enters the sea can cut its bed no lower than this baselevel, and each tributary is temporarily limited in its downcutting by the temporary baselevel of the stream to which it is tributary. Partly because the volume of water in the stream is greatest at its mouth, and partly because this is the point where it can cut deepest, the lower portion of the stream is the part where the valley develops earliest. Accordingly at, and just above, the mouth of the main streams, valley cutting proceeds apace, as it does also at the mouths of tributaries

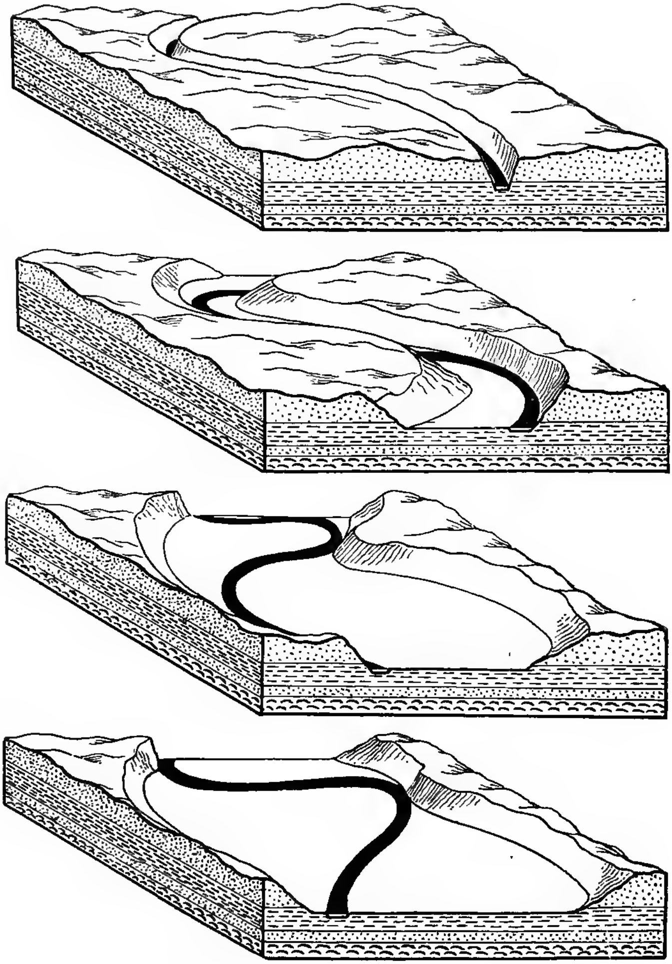


FIG. 102. — The broadening of a valley through lateral swinging by the stream.

that enter a cut channel. From these points the valley development extends up-stream farther and farther, as the downcutting in the lower portion gives the stream opportunity for excavation.

Variations in Depth. — Where such rapid downcutting is in progress, a gorge form of valley necessarily results. Whether it be a gorge of but a few feet in depth, or one of several hundred feet, will depend upon the elevation of the land surface above baselevel. The rate of the gorge formation will vary with the volume and velocity of water, and the nature of the rock to be cut away. But whether the rock be weak or resistant, the volume and velocity great or small, or the elevation high or low, the result of the excavation will be a gorge form of valley. If the rock be unconsolidated, lateral erosion will give rise to a broader form than if the rock is hard; and weathering will also be more effective in broadening the gorge.

Broadening near Stream Mouths. — Once the lower portion of a stream has reached baselevel, the gorge form wastes away slowly under the attack of rain wash and weathering. As the stream cuts down to grade, the lower valley may broaden considerably while the gorge valley is developing farther up-stream and in the headwaters.

Waterfalls and their Extinction. — In this process of downcutting, waterfalls of normal development are caused if the stream at any point discovers sufficient irregularity or resistance in the rocks of its bed; and if these irregularities are due to horizontal strata, the waterfalls slowly retreat up-stream. The consequent waterfalls developed in the earliest stages will be of short life, unless they are the result of some irregularity in rock structure which will aid in preserving them. Even though far from the river mouth, they will be removed by the

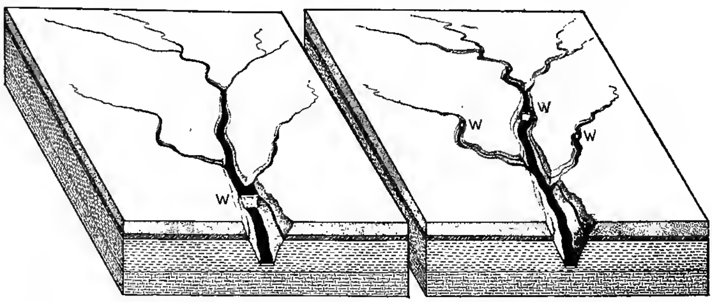


FIG. 103. — Two stages in waterfall development; the cataract at *W* retreating up-stream while smaller falls are formed in two tributaries.

more rapid cutting of the stream, resulting from the added velocity over the steep slope in which a gorge is being cut.

Lakes and their Destruction. — Each lake will serve as a temporary baselevel below which the stream above cannot cut its bed. It is, therefore, an obstacle in the way of the valley development, and will continue to be an obstacle until removed. The removal of the lake is possible in one of two ways, or by a combination of the two: (1) by cutting down at the outlet, (2) by filling with sediment. The latter will be undertaken at once by the stream if it has a sediment load, for the lake will filter this out as it checks the current that enters it. If the lake is not too large, the process of extinction by filling will be brief, as geological time goes, provided the stream can bring to it the necessary sediment. Lacking the sediment, as the Florida streams do, the destruction of the lake will require a far longer time and may have to wait for the still slower process of filling by organic remains, or until the deepening of the lower valley proceeds far enough up-stream to tap the lake, as the Niagara River, for instance, may in time be expected to do in the case of Lake Erie. In any event the lake is but a temporary phenomenon, a feature of youth in a valley and subject to extinction by one means or another as the river develops its valley toward maturity of form.

The Narrowing of Divides by Headwater Erosion. — In the earliest stages of drainage there are areas of poorly drained land and even of swamps. The divides are flat-topped and broad, and the distance between well-defined channels is great. This condition finds illustration in the broad plains between streams in the valley of the Red River of the North, and in the plains and swamps of southern Florida. As the tributaries of the main stream eat back, and as secondary tributaries develop from these, and still others from these, the flat-topped divides are narrowed, and more and more of the surface has slopes down which the run-off can flow. This extension of the tributaries is accomplished by gnawing back at the upper portion, a process that may be called *headwater erosion.*

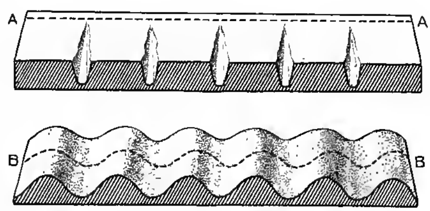


FIG. 104. — Narrowing of divides by stream development. Since the line *BB* is longer than *AA*, the slopes to be drained become greater and the stream load greater as maturity is approached.

Stream Systems like Trees. — The stream system is then passing out of the stage of youth; individual parts of it may already have passed out of this stage to that of maturity, while the smaller headwater tributaries are still developing the characteristics of youth. The condition is somewhat like that of a tree which may be broad and mature with gnarled trunk, while at the same time it sends out a multitude of fresh young twigs from each of its branches with the return of every growing season. Just so, the developing river sends out an extension of its younger headwater tributaries with the return of every heavy rain; and, as the twigs of the tree harden and mature with succeeding seasons, so the headwater valleys broaden, deepen, and mature as time goes by.

The Characteristics of Youth. — The young stream valley, whether developed on a simple plain, like the one considered, or on a much more complex surface, whether developed on lower ground or on high, has certain characteristics, so that, when one or more of these character-

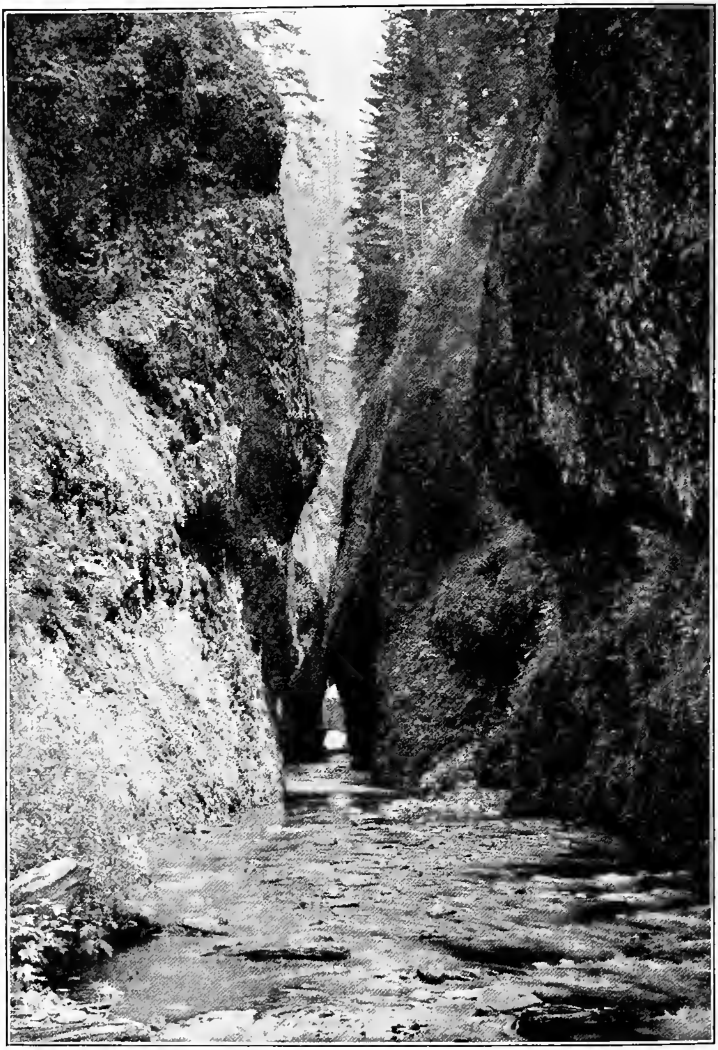


Fig. 105. — The narrow gorge or canyon of a youthful stream. This stage of youth is, of course, more advanced than that shown in Fig. 101.

istics are found in a river valley, one may with safety class it as a young valley. The characteristics of youth in river valleys are the presence of: (1) the gorge form, (2) waterfalls, (3) lakes, (4) poorly developed divides. A single one of these features is indicative of youth; and a young river valley may possess but one (Fig. 105); or it may have all four of the typical characteristics of youth.

Development of Overlapping Spurs. — In early or middle youth the gorges or canyons are usually widened sufficiently and enough curves are developed so that lateral spurs begin to be prominent. These are formed because of undercutting on one bank of the stream, which is therefore steep, and a slipping off on the opposite wall of the valley, which accordingly slopes more gently. These lateral spurs usually project alternately from opposite sides of the stream course, so that it is impossible to see a long distance down the valley. They are *overlapping spurs* (Fig. 335). As the valley broadens in late youth, the overlapping diminishes. Later the spurs may be partly buried beneath floodplain deposits.

Stream Junctions. — The entrance of tributaries into master streams obeys two general laws. First, the tributary and the main river usually form an acute angle pointing down-stream; secondly, there is no discordance in the level of main and side valleys. Both of these conditions are attained during the youth of the stream valley.

The first principle needs no amplification. The relationship is a natural one in streams consequent on slopes of the land. In original consequent drainage there are few exceptions. When the angle of junction points up-stream, however, it is usually because of some later adjustment. The latter are called *barbed tributaries*, and certain streams in the mountains (Fig. 370) illustrate this.

Except at a very early and rare stage in mountain drainage, the levels of main and side valleys are *accordant* (Fig. 151). No matter what difference there may be in the volume of tributaries, they always seem to be able to keep pace with their master streams in downcutting. One reason for this is that, although the volume of the tributary is less, its slope is steeper. Even in the Colorado River in the Grand Canyon the tributaries, which are without water part of the year, cut their gorges fully as fast as the main canyon and enter with accordant grade, as do practically all streams throughout the world in regions which have never been occupied by glaciers. More than a century ago this law was stated by Playfair as follows:

> Every river appears to consist of a main trunk, fed from a variety of branches, each running in a valley proportioned to its size, and all of them together forming a system of vallies, communicating with one another, and having such a nice adjustment of their declivities that none of them join the principal valley either on too high or too low a level; a circumstance which would be infinitely improbable if each of these vallies were not the work of the stream that flows in it.

Youth not Measured in Years. — In the use of the terms youth and maturity it is intended to convey the idea of *stage* rather than age in years. Here again comparison may be made with plants. An oak tree requires many years to reach a stage of maturity, while a young annual plant might reach the same stage in its development in a few days or weeks. Yet the stage of youth or maturity could be easily

FIG. 106. — A young valley in Italy near Naples, with houses on the gorge walls.

recognized in each case by well-defined characteristics. The case is similar with river valleys. They have notably different characteristics, and they require very different periods of time in which to develop. One valley may reach maturity in a fraction of the time required for another to reach that stage of development.

Variations with Height, Rock, and Volume. — If, for example, a stream has thousands of feet of excavation before reaching its grade, a longer time will be required for its youthful work than if it had started only a score or two of feet above baselevel. Or if the work of downcutting is performed in resistant rock, the stage of youth will linger for a longer time than if its work were in weak rock. Likewise the rate of development will be slower if the volume is slight than if it is great; and the broadening of the valley walls by weathering will proceed more slowly in an arid than in a humid climate. All these factors, and others, introduce elements of variation in rate of development of valley form, but none of them introduce conditions which will so mask the phenomena as to render it difficult to interpret them and to recognize the stage of development.

Many Stages in the Same Stream. — Owing to the different rates at which river valleys pass through the stages of development, and to causes which may arise to interfere with or modify this development, it is often the case that the different parts of a river system are in different stages of the cycle. It is necessary, therefore, to consider by itself each valley, or each section of similar history. One can rarely say that a large river system is young, or mature, though it is usually not difficult to classify any given part of it.

Mature Valleys

Contrasts with Youth. — The development of maturity of valley form is but a continuation of the processes outlined in the preceding section. The lakes have been filled; the waterfalls have disappeared; and the river has attained a grade approximating the lowest slope over which its sediment load can be transported. By the gnawing back of the headwater tributaries the land is now all provided with slopes down which the water may run, and channels along which it may go from one tributary to another. The divides are narrowed and the region is traversed by a complex network of valleys. Weathering and rain wash are now the main elements in the denudation of the land, and the streams have for their main task the drainage of the land and the removal of the sediment turned over to them. Otherwise their work of valley formation is practically at an end, though here and there, by swinging against their valley walls, they may be engaged in actual work of excavation by lateral erosion.

The Correction of Grade. — While in this stage the streams have approximated grade, and in places have reached it, there are two sections where the grade is still in process of establishment. One of these is in the upper reaches, where the streams are still cutting in their beds, and where their valleys may even be still in the state of youth, with gorges and waterfalls. The other is in the lower and middle course, where the stream may be engaged in correcting a too low grade, established earlier in the cycle. As the slopes develop by headwater erosion, a larger burden of sediment may come to the

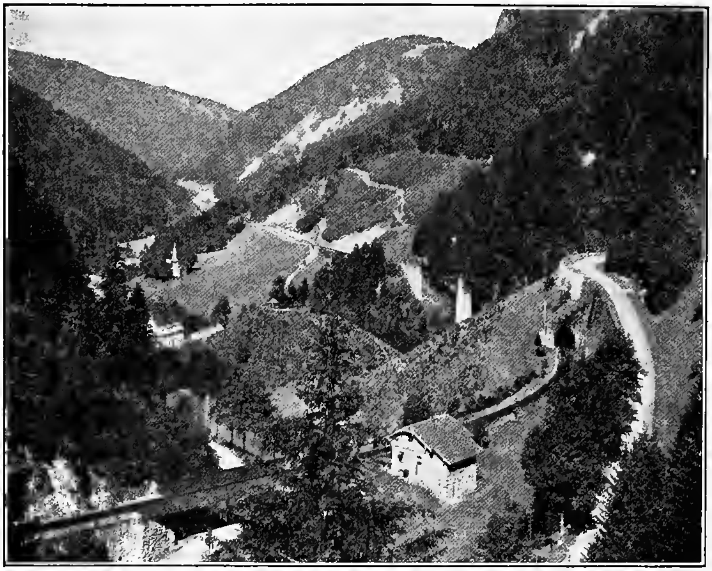


FIG. 107. — A stream valley in late youth or early maturity.

stream, and this it may not be able to move over the lower grade established during the stage of late youth or early maturity. In that case the stream aggrades its lower course, and floodplains develop, which are made even more extensive if the stream builds a delta at its mouth. The correction of the grade lower down in the river valley necessitates a correction above, in order to maintain an adequate slope. Thus floodplains develop along a large part of the mature river, and over them the river swings in a meandering course (Fig. 109).

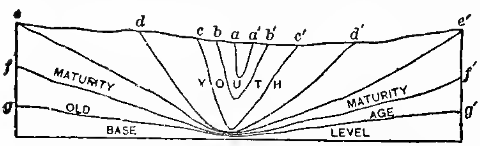


FIG. 108. — Cross section of a valley in various stages of youth (*aa'* to *cc'*), of adolescence (*dd'*), of maturity (*ff'*), and of old age (*gg'*).

The Characteristics of Maturity. — Floodplains and meandering streams are among the characteristics of maturity of stream valley development. Other characteristics are moderately sloping valley walls, a well-defined drainage system with many tributaries and defi-

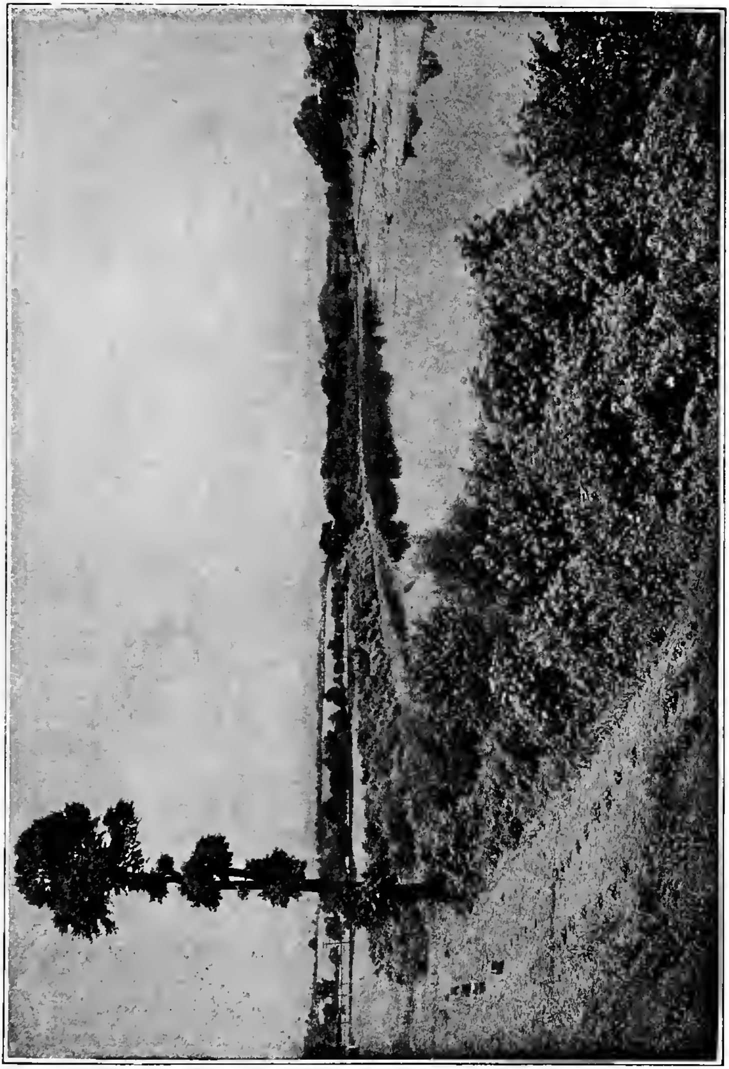


Fig. 109.—A mature valley in Pennsylvania.

nite divides, a fairly well-established grade, and the absence of waterfalls and lakes. The degree to which these characteristics are developed depends upon the part of the stage reached; that is, they are only partly developed in the stage of early maturity, but are fully developed in the stage of full or late maturity. It has been proposed to call the state of early maturity the stage of *adolescence* (Figs. 107, 108).

Old Valleys

Slow Development after Maturity. — Youth is a relatively rapid stage of valley development, maturity is longer, but old age is of almost infinite duration. Accordingly, since the surface of the earth is subject to changes of other kinds, it must be rare for valley development to proceed with such slight interruptions as to permit any considerable portion of the earth to attain the condition of old age. Few river valleys of to-day are in the stage of old age, and most of them are in youth or early maturity. Before time has sufficed for their development beyond this stage, some change, such as uplift or depression, so interferes with their development as to start them on a new cycle. Yet in past ages there have been periods during which the old age stage has been reached and the remnants of some of these are recognizable in the topography of to-day. This seems to

Fig. 110. — The peneplain of southern New Hampshire, with Mt. Monadnock.

argue for periods of greater earth stability during certain ages of the past than at present and in the recent past, a conclusion toward which other facts also point.

The Characteristics of Old Age. — In the old age stage the valley slopes are worn to even less relief than that of full maturity. The water runs off from them less readily, and more is lost by evaporation, so that the river volume diminishes. There is also a decrease in sediment load, and that which is supplied is of finer grain than in earlier stages. A larger proportion of the mineral load of the river is carried in solution, and the wasting away of the gentle slopes is mainly performed by the solvent action of underground water. Broad flood-plains still border the rivers, and over the flat valley bottoms the rivers still flow in broadly meandering courses.

Peneplains. — Old age differs from maturity in far less notable ways than maturity does from youth. The prime difference is the decreased valley slopes; and after they have passed the stage of sufficient steepness for the inwash of considerable quantities of sediment, their further lowering must be a process of exceeding slowness. A land form, whether plain or mountainous, thus worn down to the moderate slopes of the old age stage, is a *peneplain* (Fig. 110 and Pl. X).

Variations in Valley Forms

Causes of Variations. — From the simple, ideal case of development in which uniformity is assured, there are wide variations in several directions, one of them being in the form of the valley. If excavated in rock of uniform texture, the valley slopes are simple, varying with the nature of the rock, the climatic conditions, the elevation, the volume of water, and the stage of development; but if excavated in rock of varying texture, the slopes are complex during the stages of youth and early maturity, though with advancing maturity the influence of the rock on valley form becomes of decreasing importance.

Lateral Terraces in Horizontal Rock. — This influence of varying rock texture may be illustrated by two cases, one in which the strata vary horizontally, the other in which they vary vertically. In the first case the strata are horizontal. Successive differences in rock resistance are discovered as the stream cuts its way down into the strata. In the stream bed these give rise to waterfalls, as we have seen, but on the valley walls they give rise to rock terraces. By the differential weathering the hard layers are etched into relief, and the valley sides are terraced, as is so well illustrated in the Colorado canyon. If the differences are but slight, and the layers of different texture thin, the terracing may be of only moderate degree; but if the beds are thick, and the differences great, extensive rock benches and escarpments may develop. With increasing maturity these recede farther and farther from the stream, often for many miles, until finally, as the slopes are more and more reduced, resistant beds no longer reveal themselves in the topography, but are covered with a mantle of rock waste.

Narrow Gaps and Broad Valleys in Vertical Structures. — Where the strata are vertical, the resistant strata are also etched into relief, while the weaker strata are more rapidly worn away. As a result of this process the valley alternately broadens and narrows, each narrow place being where the stream is crossing a resistant bed, and each broad place where it cuts across the weaker strata. Here also the influence of the variations depends upon the extent of the difference in resistance, and upon the width of the varying strata. With valley development these differences become less and less noticeable.

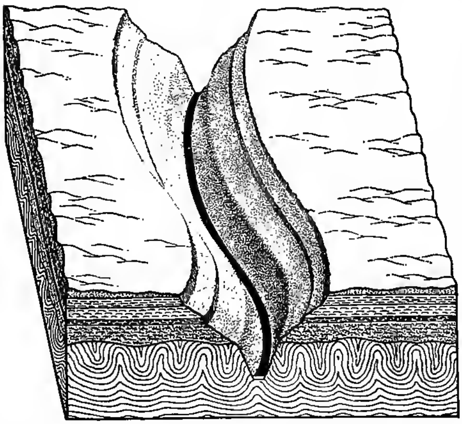


FIG. 111. — A superimposed river, which has cut down through the horizontal structures of a plateau to the folded structures of a worn-down and buried mountain mass.

Superimposed Streams. — It sometimes happens that a stream flowing upon a land surface of given kind, such as a plain or a plateau, discovers a very different structure as it cuts its channel toward grade. Thus the Colorado River, after cutting several thousand feet in the horizontal strata of the plateau, has discovered a buried, worn-down mountain area upon which the plateau rests. Into this it is now cutting a part of its course. Such a river is *superimposed*, and the kind of valley that develops may be very different from that which developed before the discovery. Thus the Colorado flows in a narrow, steep-walled canyon where it crosses the buried mountain rocks, with their steeply inclined, variable, and resistant strata, while in the upper portion the valley is terraced by the etching out of the horizontal strata of the plateau (Figs. 111, 112).

VARIATIONS IN STREAM COURSE

Subsequent Streams. — In the ideal case the stream courses were consequent upon the topography that the running water discovered; and such must always be the course of a stream upon a new land. But during the ages required for the passage of a stream valley through its cycle of development, the stream may undergo very notable changes in position and depart very widely from the original consequent course. Such a course, developed by subsequent changes, is a *subsequent* course, in distinction from the original consequent course.

There is a wide variety of conditions which may give rise to such changes in a stream course, only a few of which are considered at this point, while others are taken up in later sections. The original consequent course may, for example, be very irregular and roundabout, and during its development such a course will tend to be straightened. Or the original course may be straight, and with subsequent development meandering will be set up.

Adjustment to Rock Structure. — Among the causes for change of course of streams is that of adjustment to rock structure. The original course is determined by topography, not by rock structure, unless that has determined the topography. It may happen, therefore, that a consequent stream is flowing on resistant rock, while not far away there are much weaker beds. As the surface wastes away and a valley develops in the weaker beds, the consequent course may be abandoned for a subsequent course along the weaker rock. Such a stream is *adjusted*. By the time maturity of valley form is reached, there is perfect adjustment to rock structure, and the adjusted course may depart widely from the original consequent course. Usually subsequent tributaries develop at right angles to a consequent master stream. This angular pattern of stream courses (Fig. 366) is known as *trellis drainage*.

FIG. 112. — The Colorado Canyon with horizontal sedimentary rocks above and highly folded metamorphic rocks below, where the river is superimposed upon the older strata. (U. S. Geol. Survey.)

The Shifting of Divides. — In the wearing down and adjusting of stream courses, headwater erosion by adjacent streams is usually unequal. This is because of the advantage which (*a*) increased volume, (*b*) lower baselevel, or (*c*) weaker rock gives one stream over its neighbours. Consequently headwater erosion not only reduces divides in altitude, but also causes them to shift horizontally (Fig. 359). In regions of inclined sedimentary rocks the streams obey a general law, which is that *the divide migrates in the direction of the dip*. When local warping of a land surface takes place, the law, worked out by Campbell, is that the divide will migrate toward an axis of uplift or away from an axis of subsidence.

Stream Piracy and Diversion. — One important event in the adjustment of stream course is the diversion of one stream by another. There are a variety of ways in which this may be brought about, a consideration of which is for the present deferred. Suffice it here to say that, if one stream finds conditions more favourable for development than another neighbouring stream, it may, by the extension of branches or of headwaters, eat back until it taps a part of the less favourably situated stream and diverts it to its own channel. Such robbery has been called stream piracy, and the diverting stream has been called a *river pirate.* A less sensational, and, on the whole, probably a more definitive, term is *diverting* stream.

For these and other reasons a stream course as well as a stream valley is subject to change. During a human lifetime both valley form and stream course appear to be fixed and unchangeable; but, viewed from the standpoint of geological time, the stream and stream valley are the seat of incessant change, following laws which are usually not difficult to discover and interpret.

Insequent and Obsequent Streams. — Streams in which no adjustment to rock structure takes place, either (*a*) because of widespread flat-lying sediments, or (*b*) because the stream develops in a large area of a massive formation such as granite, never have subsequent tributaries. This is because the adjustment is complete from the beginning. This *insequent* stream pattern is often treelike, for which reason the drainage is said to be *dendritic* (Fig. 366).

When, however, adjustment to inclined sedimentary beds results in subsequent tributaries of consequent master streams which happen to flow originally across the trend of the rock structure, still another type of stream is formed. The subsequent tributaries will themselves receive affluents. Those which flow in the opposite direction from the original consequent drainage are called *obsequent* streams. They develop especially upon the escarpments of belted coastal plains, as explained later (Chap. XIV).

Climatic Relationships. — Rivers that flow out into deserts diminish in volume down-stream and eventually disappear. This is a climatic relationship. Rivers that flow northward, like the Mackenzie and Yukon in America and the Siberian rivers in Asia, have a seasonal climatic relationship to winter ice. This is not well understood, but some of these streams must have their activity in erosion, transportation, and deposition distinctly limited by the short season. Many small rivers are frozen clear to the bottom when, of course, all work ceases. As long as the ground is frozen they receive little sediment, though run-off is increased by the prohibition of percolation. Ground ice as well as frost in the ground later add to the summer volume of such streams. Even in temperate climates some streams flow through ice-walled gorges temporarily. While the ice is frozen to the river bottom they may even flow over floors of ice. Then, of course, their erosive power is limited, but this latter is only a local and exceedingly temporary climatic relationship of rivers.

Variations due to Accidents and Interruptions

The Accident of Glaciation. — Both the work of a stream in valley formation and the course of the stream may suffer interference for a long time by accidental causes. The spread of an ice sheet over a country, for instance, for the time being exterminates streams; and upon its withdrawal the surface of the land may be greatly modified. Streams may be turned out of their old valleys and forced to develop new ones, thus locally assuming the features of youth, though in other parts occupying a valley whose stage of development was attained before the ice invasion. Streams may even find their courses over an entirely new land surface, and be forced to start upon a new cycle, as the Niagara River has done.

Other types of accidents occur in connection with temporary aridity, with lava flows, landslides, etc.

Interruptions and Rejuvenated Streams. — By such interruptions of valley development there are all gradations from conditions in which the stream is only locally, or slightly, or temporarily modified to those under which the cycle must start anew. All these latter changes, involving a change of baselevel by uplift or by submergence, are technically known as *interruptions*. A stream interrupted by uplift is said to be *rejuvenated*.

The rejuvenated stream, though inheriting some of the features of the earlier cycle, is given renewed opportunity for valley development, as a result of which it assumes some or all of the characteristics of youth in a whole or a part of its course. The uplift of the land, or the tilting of the land so as to increase the stream grade, will always, if extensive enough, set the stream at work again cutting its bed, and a gorge will be excavated in the bottom of the old valley. Such a stream may be said to be *revived* or rejuvenated.

The Rejuvenated Rhine. — This condition is well illustrated by the Rhine and some of its tributaries in Germany. Below Bingen the river flows through a young gorge transecting a complex series of inclined strata, and tributaries to it also flow in gorges in which there are often rapids and falls (Fig. 113). The uplands between the gorges, and bordering the Rhine, are a succession of moderately undulating hills and valleys, a topography of advanced maturity or old age in which the revived Rhine and its tributaries have sunk their gorges. The upland is, in fact, a peneplain, developed by the wearing down of a mountain region, and now being dissected by rejuvenated streams. The upland slopes are so gentle as to be

FIG. 113. — The gorge of the Rhine.

occupied by farms; but the young valleys cut in it are so steeply sloping that only the largest have cultivated slopes, and these only after great labour has been expended in terracing the steep slopes.

Rejuvenation after Maturity. — A stream rejuvenated in the stage of youth would probably show little evidence of the rejuvenation

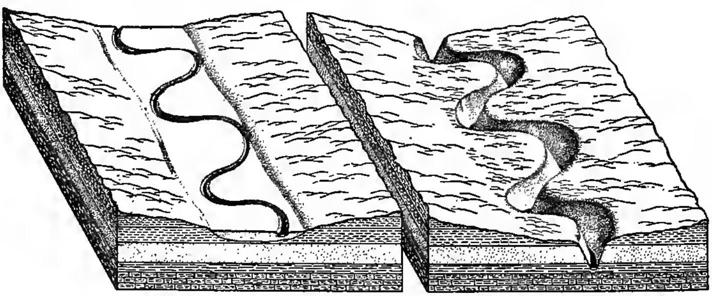


FIG. 114. — The origin of entrenched meanders.

in the valley form; but a rejuvenated mature or old valley would preserve some of the inherited earlier features, as the Rhine inherits the old valley in which the present gorge has been sunk. Another inherited characteristic may be the meandering course which a mature river normally has on its floodplain. When the meandering stream commences to cut its gorge as a result of rejuvenation, it may still preserve the meandering course although entrenched in the rock. Such a course is called *entrenched* or *incised*, and the meanders are called *entrenched meanders* or *incised meanders* (Figs. 114, 115). A meandering course, closely resembling that of a floodplain river, could not develop in a rock gorge, because the swinging which gives rise to

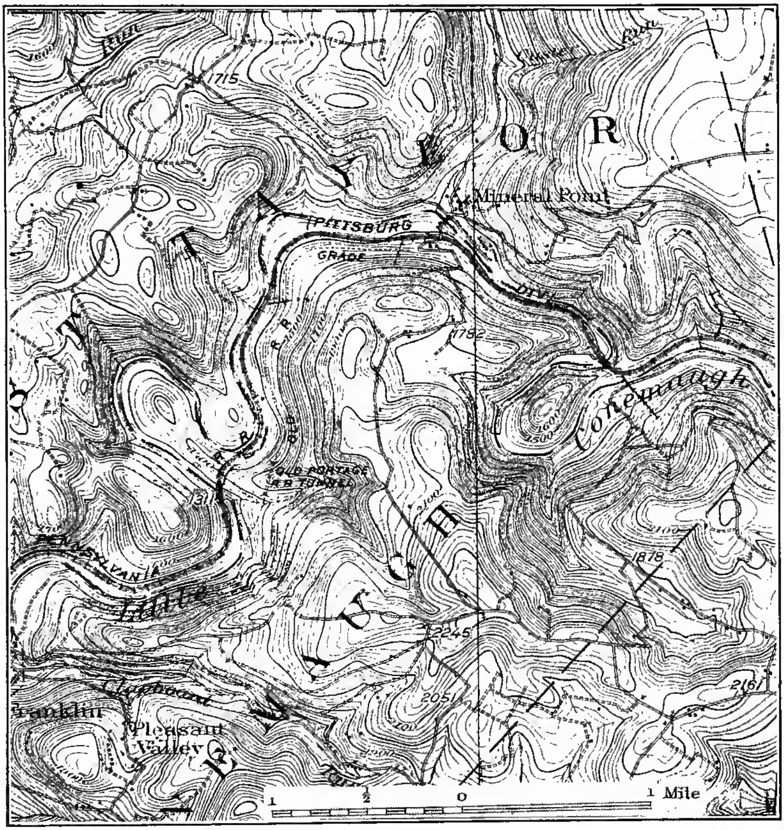


FIG. 115.—Entrenched meanders in the Allegheny Plateau of Pennsylvania. (Johnstown Quadrangle, U. S. Geol. Survey.)

the meandering would need first to cut the gorge walls away; and incised meanders are closely bordered by the gorge walls on both sides, the walls themselves swinging to parallel the meandering river. Such a condition is possible only as a result of an inherited course entrenched by corrasion.

Illustrations of Entrenched Meanders. — There are many instances of incised meanders. The Susquehanna in southern New York and northern Pennsylvania is a typical illustration, and the Moselle in western Germany is another. Some of the meanders of the Moselle are perfect ox-bow forms, and one can look down from the neck of the ox-bow to the river on both sides, as one can from the narrow neck of a floodplain ox-bow; but in the Moselle the river flows between steeply rising valley walls, and the ox-bow is a rock hill, not a low alluvial plain just above the river level. During the process of entrenching, the lateral cutting of the stream has in some cases worn through the neck of the ox-bow and made a cut-off, through which the stream flows, abandoning the old course and leaving a rock hill completely encircled by a valley. Such a cut-off hill rises in the Susquehanna valley near Binghamton. It is by the undercutting of the rock at the neck of such an incised ox-bow that some of the huge natural bridges of Utah have been formed.

Extended Rivers. — Uplift of the land often raises parts of the sea bottom and adds them to the continents. Over such land the streams are *extended*, and independent streams may there unite, one stream being *ingrafted* on another. Such a condition is common on coastal plains, and has developed in numerous instances along the coastal plains of southern United States.

Drowned Valleys. — On the other extreme, a depression of the land may dismember streams by drowning the lower part of a valley, and causing the tributaries to enter the sea along separate courses. A valley which has had this fate is a *drowned* valley. The northeastern coast of the United States and the northwestern coast of Europe offer innumerable instances of such *estuaries*. Chesapeake Bay is a typical instance, and so is the Baltic Sea. Before submergence, the streams which now enter these bodies of water through separate mouths entered the sea through a trunk stream to which they were tributary. If the land should be uplifted again, raising the shallow beds above sea level, the streams would have their courses extended and would become ingrafted upon the trunk stream.

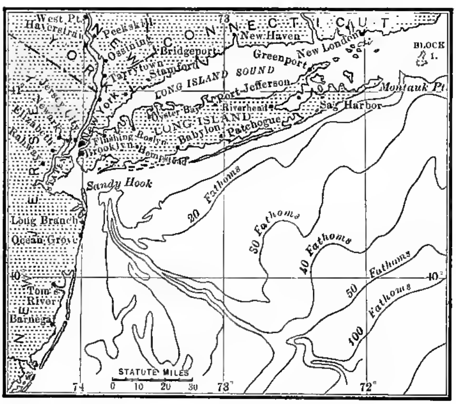


FIG. 116. — The course of the drowned lower Hudson River southeast of New York.

The Effects of Depression. — While elevation of the land gives new life to a stream, depression tends in the opposite direction, for it lowers the level of the land that must be reduced by denudation by a relative rise in the baselevel. Locally depression may revive a stream by bringing the baselevel so far up-stream that the slope is greater than is needed; but such a change produces so slight an effect that it may be ignored.

Tilting and Local Uplift. — The effects of elevation and depression have so far been considered as if they were uniform in amount throughout the stream; but there are three possible and important ways in which there may be variation from such uniformity. The first of these is a tilting, increasing the slope toward the sea, which naturally intensifies the effect of the uplift by giving the stream greater power for excavation. The second is a tilting in the opposite direction by which the slope is diminished, and therefore the power of the stream possibly decreased. Such a tilting might conceivably proceed so far as to even reverse the direction of stream flow on a small land surface occupied by weak streams.

The third variation is by local uplift across the stream course. If the rate of local uplift is too rapid, or the stream too weak to cut its bed as fast as the uplift proceeds, the stream may be transformed to a lake by the growth of a dam, and its course may be diverted or even reversed. Such is probably the usual result when mountains rise across a stream course; though there are some stream courses across mountains which may have existed before, or be antecedent to, the mountain uplift. Such a stream course is said to be *antecedent.*

Illustrations of Antecedent Streams. — This explanation has been applied to a number of cases of rivers crossing mountain ridges or parts of ranges, such as the Green River across the Uinta Mountains of Utah and the Sutlej in the Himalayas; but in most such cases the explanation is very doubtful, if not quite disproved, as in the case of the Green River. On the other hand, the Rhine where it crosses the highlands of central Germany, the Meuse in the highland of Ardennes in northern France, and the Kanawha River where it crosses the plateau of West Virginia seem to be true instances of antecedent rivers.

Incomplete Cycles of Erosion. — Thus it is clear that, although the normal tendency is for river valleys to pass through a cycle of development from youth to maturity and old age, there are other conditions operating upon the surface of the lands by which this cycle of development is liable to interruption. And, since the cycle of development is a long one, rivers in one part or another of their course are certain, sooner or later, to experience some influence by which the cycle is interfered with. The age of the earth is so great that, had the cycle of valley development proceeded uninterruptedly, the lands of all the continents would long since have been wasted away to the condition of advanced old age. Instead of that, we have on the continents the pleasing topographic variety, and the great complexity of surface forms that bear the stamp of river work in all stages of valley development and of development interrupted, retarded, and accelerated by a multitude of accidents and interruptions of different origins and with different results.

Underground Rivers

Relation to Surface Drainage. — In this chapter drainage has been treated as a surface phenomenon; but it has previously been shown that there is also an underground drainage with important results. One phase of the underground drainage, where solution is enabled to play an important rôle, gives rise to a system of subterranean waterways, which at times are large enough to deserve the name underground rivers.

Contrasts with Ordinary Rivers. — These underground rivers differ widely from surface rivers in many important respects. The underground valley is a rock-walled and rock-roofed cavern; its form and direction are irregular and unsystematic, as are its tributaries; there is little broadening by weathering; there are no floodplains and no deltas, for the sediment load is slight; and, since solution is the prime factor in the development of the underground course, the life history of the cavern valley is wholly unlike that of a surface valley.

The underground river is a special phase of percolating water, enlarged in volume as a result of development under favourable conditions. It is, however, somewhat more than this, for although a part of its supply comes from percolation into the ground, and is, therefore, normal underground water, another part is water that, after a course of greater or less length on the surface, disappears abruptly into the ground and thence onward follows the underground course until it emerges again as a spring. From this standpoint underground rivers may be classed as a special kind of river, and where entering other rivers, as a special phase of river tributary.

There is, in fact, every gradation between the surface river and the underground river, for many surface streams disappear into the ground, and some have only very short underground courses, even no more than the passage beneath a natural bridge a few feet in width. The ultimate fate of the underground course is to be exposed at the surface when the limit of downcutting is reached, and when weathering lowers the surface to it.

Influence of Valley Stage on Habitation

Favourable Conditions in Extreme Youth. — In the immature stage of valley development the level land invites settlement and agriculture where soil and climate are favourable. Thus coastal plains, the plains of the Red River of the North, and other land surfaces, upon which the drainage has not been long established, may be the seat of an agricultural population. Where the surface is too level the early state of drainage may leave the land so wet that, as in the Everglades of southern Florida, it is uninhabitable without artificial drainage.

Young Gorges Unfavourable to Man. — During the youthful stage of valley development, the flat-topped divides between the few streams are still good farm land, and although swamps may still exist, they are, in the main, better drained than in the earlier stage. The valley bottoms are not inviting places for human habitation, for

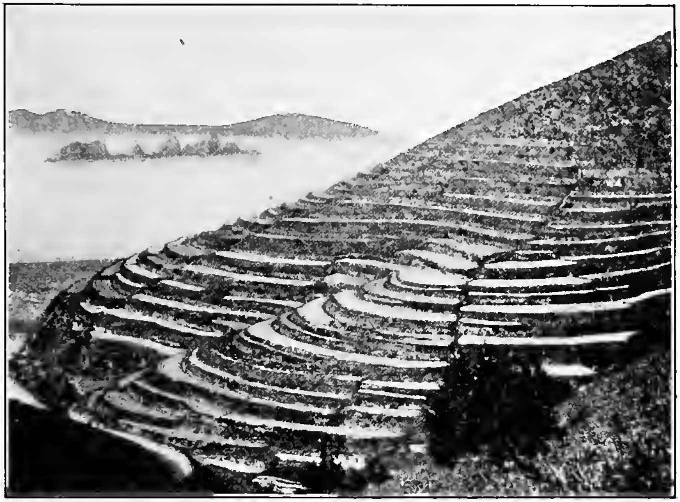


FIG. 117. — Slopes so steep that they must be terraced in order to be cultivated. Scene in China.

they are too narrow and too steeply enclosed. Nor are they, as a rule, feasible routes of travel, for their slope is variable, and often too steep, while their narrowness and the swinging of the stream against their walls, first on one side, then on the other, are opposed to passage up or down the gorge valleys. Young valleys are also obstacles to travel across country, for they interpose narrow gashes across the route, down whose steep slopes it is difficult, if not impossible, to descend, and across which it is expensive to place bridges.

Uses of Streams in Gorges. — The water power is valuable; but, being often deeply set in a valley between gorge walls, it has not always been possible to utilize it. Now that it can be transformed to electric power, more and more of this hitherto inaccessible water power is being utilized. In arid lands the water in young stream valleys is difficult to utilize for irrigation, for it may be scores or hundreds of feet below the level of the land through which the stream is flowing.

Mature Valleys most Favourable to Habitation. — Mature valleys, with their floodplains and moderately sloping valley walls, are inviting to settlement, for the land can be cultivated, and the grade and breadth of the valleys lead to their use as routes of travel, which become even more important if occupied by a navigable river. Towns and cities develop along the larger valleys, often at the junction of tributaries along which other routes extend, making the junction of the valleys a centre of converging highways.

Among the headwaters, especially during the stage of early maturity, the many minor tributaries, as they gnaw their way back by headwater erosion, so dissect the land that it is a hilly region, perhaps too rough for farming and, therefore, still given over to forest, or possibly utilized for grazing. This is the condition of much of the plateau which skirts the western base of the Appalachians and extends westward into Ohio, Kentucky, and Tennessee. With advancing maturity this hilly condition disappears and the surface becomes more and more even and suited to agriculture. A region of full maturity is one of slopes sufficiently moderate for agriculture in practically all its parts. Full maturity and old age are the most favourable stages of valley development for man's uses.

References to Literature

R. E. Browne. Ancient River Beds of Forest Hill Divide, 10th Ann. Rept. California State Mineralogist, 1890, pp. 435–465.

M. R. Campbell. Drainage Modifications and their Interpretation, Journ. Geol., Vol. 4, 1896, pp. 567–581, 657–678; Tertiary Changes in the Drainage of Southwestern Virginia, Amer. Journ. Sci., Vol. 148, 1894, pp. 21–29; Erosion at Baselevel, Bull. Geol. Soc. Amer., Vol. 8, 1897, pp. 221–226.

H. P. Cushing, H. L. Fairchild, R. Ruedemann, and C. H. Smyth, Jr. Geology of the Thousand Island Region, Bull. 145, N. Y. State Museum, 1910, 194 pp.

R. A. Daly. The Accordance of Summit Levels among Alpine Mountains, Journ. Geol., Vol. 13, 1905, pp. 105–125.

W. M. Davis. The Stream Contest along the Blue Ridge, Bull. Geog. Soc. Phila., Vol. 3, 1905, pp. 213–244; Incised Meandering Valleys, *ibid.*, Vol. 4, 1906, pp. 182–192; Geographical Essays, Boston, 1909, including "The Seine, the Meuse and the Moselle"; "Baselevel, Grade, and Peneplain"; "The Peneplain"; "Plains of Marine and Subaërial Denudation"; "The Geographical Cycle"; "Complications of the Geographical Cycle"; "The Geographical Cycle in an Arid Climate"; "The Rivers and Valleys of Pennsylvania"; "The Rivers of Northern New Jersey"; and several other papers.

H. M. Eakin. The Influence of the Earth's Rotation upon the Lateral Erosion of Streams, Journ. Geol., Vol. 18, 1911, pp. 435–447.

S. F. Emmons. Uinta Mountains, Bull. Geol. Soc. Amer., Vol. 18, 1907, pp. 287–302.

G. K. Gilbert. Land Sculpture, in Geology of the Henry Mountains, U. S. Geographical and Geological Survey of the Rocky Mountain Region, Washington, 1877, pp. 99–150; The Sufficiency of Terrestrial Rotation for the Deflection of Streams, Memoirs Nat. Acad. Sci., Vol. 3, 1885, pp. 7–10; The Convexity of Hilltops, Journ. Geol., Vol. 17, 1909, pp. 344–350.

J. W. Goldthwait. Physical Features of the Des Plaines Valley, Bull. 11, Illinois Geol. Survey, 1909, 103 pp.
J. P. Goode. The Piracy of the Yellowstone, Journ. Geol., Vol. 7, 1899, pp. 261–271.
D. W. Johnson. The Tertiary History of the Tennessee River, Journ. Geol., Vol. 13, 1905, pp. 194–231; Drainage Modifications in the Tallulah District, Proc. Bost. Soc. Nat. Hist., Vol. 23, 1907, pp. 211–248.
H. B. Kümmel. Some Rivers of Connecticut, Journ. Geol., Vol. 1, 1893, pp. 371–393.
W. T. Lee. Canyons of Southeastern Colorado, Journ. Geog., Vol. 1, 1902, pp. 357–370; Canyons of Northeastern New Mexico, *ibid.*, Vol. 2, 1903, pp. 63–82.
W. Lindgren. The Tertiary Gravels of the Sierra Nevada, Prof. Paper 73, U. S. Geol. Survey, 1911, 226 pp.
F. Löwl. Über Thalbildung, Prague, 1884.
Lawrence Martin. The Physiography of the Lake Superior Region, Monograph 52, U. S. Geol. Survey, 1911, pp. 85–117; The Physical Geography of Wisconsin, Journ. Geog., Vol. 12, 1914, pp. 226–232.
A. Philippson. Studien über Wasserscheiden, Leipzig, 1886, 162 pp.
F. von Richthofen. Führer für Forschungsreisende, Berlin, 1886.
N. S. Shaler. Spacing of Rivers with Reference to Hypothesis of Baselevelling, Bull. Geol. Soc. Amer., Vol. 10, 1899, pp. 263–276.
W. S. T. Smith. Some Aspects of Erosion, Bull. Dept. Geol., Univ. California, Vol. 2, 1899, pp. 155–178.
W. H. Storms. Ancient Channel System of Calaveras County, 12th Ann. Rept., California State Mineralogist, 1894, pp. 482–492.
R. S. Tarr. The Peneplain, Amer. Geol., Vol. 21, 1898, pp. 351–370.
C. R. Van Hise. A Central Wisconsin Baselevel, Science, N. S., Vol. 4, 1896, pp. 57–59; A Northern Michigan Baselevel, *ibid.*, pp. 217–220; The Origin of the Dells of the Wisconsin, Trans. Wis. Acad., Vol. 10, 1895, pp. 556–560.
C. A. White. On the Geology and Physiography of Northwestern Colorado and Adjacent Parts of Utah and Wyoming, 9th Ann. Rept., U. S. Geol. Survey, 1889, pp. 677–712.
A. W. G. Wilson. The Laurentian Peneplain, Journ. Geol., Vol. 11, 1903, pp. 615–669.

TOPOGRAPHIC MAPS

Arid Land Drainage

Higbee, Colo.	Kaibab, Ariz.	Watrous, N.M.
Boise, Idaho	Alturas, Cal.	East Tavaputs, Utah
Sierraville, Cal.	Disaster, Nev.	Paradise, Nev.
Granite Range, Nev.	Tooele Valley, Utah	Salt Lake, Utah

Mature and Old Valleys

Elmira, N.Y.	Kaaterskill, N.Y.	Gaines, Pa.
Briceville, Tenn.	Scottsboro, Ala.	Salyersville, Ky.
Huntington, W.Va.	Charleston, W.Va.	Cohoes, N.Y.
Springfield, Mass.	Becket, Mass.	Monadnock, N.H.
Hartford, Conn.	Mt. Marcy, N.Y.	Winslow, Ark.
Monterey, Va.	Fort Payne, Ala.	Estillville, Ky.
Franklin, W.Va.	Maynardville, Tenn.	Hazelton, Pa.
Lykens, Pa.	Atlanta, Ga.	New Haven, Conn.
Skaneateles, N.Y.	Caldwell, Kan.	Ovid, N.Y.

Migrating Watershed

Kaaterskill, N.Y.	Gloversville, N.Y.	Hamilton, Idaho

Mountain Gorges

Platte Canyon, Colo.	Livingston, Mont.

Post-glacial Young Streams

St. Paul, Minn.	Cohoes, N.Y.	Skaneateles, N.Y.
Niagara Gorge, N.Y.	Lacon, Ill.	Rochester Special, N.Y.

Rejuvenated Streams and Entrenched Meanders

Lockport, Ky.	Salyersville, Ky.	Charleston, W.Va.
Palo Pinto, Tex.	Johnstown, Pa.	Palmyra, Va.

Stream Adjustments

Delaware Water Gap, Pa.	Kaaterskill, N.Y.	Hollidaysburg, Pa.
West Point, N.Y.	Harrisburg, Pa.	Monterey, Va.
Piedmont, W.Va.	Caddo Gap, Ark.	Fort Payne, Ala.
Bristol, Va.	Lykens, Pa.	Antietam, Md.

CHAPTER VIII

GLACIERS AND GLACIATION

Water in its Solid Form

Water at Freezing Temperatures. — At the freezing point, 32° F. (0° C.), fresh water assumes the solid form, and its properties and the work which it performs are then completely changed. Water in its solid form can be of importance only in those climates where the temperature descends below 32° for a part of the year; and it becomes increasingly important as the period during which such temperatures prevail lengthens. The parts of the earth where this condition obtains are (1) high latitudes, (2) high altitudes.

The Freezing of Ground Water. — With a temperature below the freezing point it is possible to have a variety of different forms of solidification of water, and consequently of different kinds of work performed. The ground water, for example, becomes frozen and, as we have seen in the study of weathering, performs powerful work in rock disintegration. For the time being it solidifies the soil with an icy cement, interfering with percolation and with erosion. Expanding in the soil, it pushes fragments about, even thrusting good-sized fragments upward.

Ice Work in Rivers. — Rivers are frozen at their surface, and ice is formed even on their beds, aiding in removal of rock fragments. On melting it turns loose, in liquid form, the water that has been temporarily locked up in the solidified state. As has been stated in the discussion of rivers, the formation of ice is an important factor in the erosive work of river water.

Ice in Lakes. — Ice forms also on the surface of lakes, but only the shallowest freeze to the bottom. This is because fresh water, on growing colder, becomes heavier and sinks to the bottom until the temperature of about 39° F. is reached, after which further cooling makes it lighter. The lake cannot freeze over until the whole mass, from top to bottom, has had its temperature lowered to 39°, and then the surface layer lowered to 32°. When the ice forms, it expands and is lighter than the water and, therefore, floats. It assumes a crystalline form on freezing. The crystals are of the hexagonal form with their axes extending vertically. Lake ice, as well as river ice, has geological work to perform, as will be shown later.

Sea Ice. — Even the sea, in very cold climates, freezes at the surface; but salt water behaves very differently from fresh. Its freezing point is 27° or 28°, according to its salinity, and it continues to contract and grow heavier until the freezing point is reached, when it expands and the ice floats, as in lakes. During the freezing the salt is not included in the ice crystals, but is left as brine in the interstices. Therefore the ice tastes salt. The work of sea ice is treated later.

Other Solid Forms of Water. — Water is also present in the atmosphere in the form of water vapour, and when the temperature of the air descends below the freezing point, some of it will be transformed to the solid state if the proper point of humidity is reached. It may come out as frost on the ground, or, under certain conditions, as hail, or as snow or sleet. The hail and sleet may in some cases be frozen raindrops, but the snow is a crystal form which vapour assumes as it condenses to solid state in the air. The crystals grow by additions of molecules of vapour and often assume beautiful starlike form, as the crystals grow under the hexagonal system. In their descent they may be broken, or matted together, or partly melted and frozen.

The Work of Snow. — Falling to the ground, the snow crystals form a blanket of snow, whose thickness varies from place to place and from season to season. Some of the snow disappears by evaporation, but in most regions the snowfall is dissipated mainly by melting during the return of warm weather, either during the course of the winter or at its close. Then, in the form of running or percolating water, it enters into the activities which have been considered in preceding chapters. While it lies upon the ground in solid form, the snow is usually inert and ineffective as an agent of change; it serves as an agent of protection both to the land and to the plant and animal life which it covers with a blanket of such poor conductivity that it serves to maintain a far more uniform temperature than the bare surface could have during the changes of day and night and from day to day. Upon melting it springs into high activity, and becomes an agent of erosion. Even in the solid state, snow is an agent of erosion where it lies on slopes of sufficient steepness to permit it to slide away in avalanches.

Snow Fields

The Height of the Snow Line. — When the snowfall is in excess of melting and evaporation, a blanket of snow remains the year round. The line above which the snow remains permanently on the ground is called the *snow line.* The level of the snow line varies greatly with the latitude, for one of the chief factors in determining it is temperature. In the Antarctic, and in parts of the Arctic, it lies at sea level, but in the tropical zone it is from 14,000 to 20,000 feet above sea level. Therefore, most lofty mountains rise above the snow line. In the Andes the snow line is reached at 16,000 to 18,000 feet in Bolivia, but it descends to 1600 feet in southern Chile. In Mexico the snow line lies at an elevation of about 15,000 feet, but descends to less than 3000 feet in Alaska. No part of eastern North America rises above

TABLE SHOWING ELEVATION OF SNOW LINE IN DIFFERENT LATITUDES (AFTER PASCHINGER)

LATITUDE	PLACE	HEIGHT IN FEET
80°–70° N.	Franz Josef Land	1,000
70°–60°	Iceland	1,800
60°–50°	Coast of Alaska	2,500
50°–40°	British Columbia	4,600
40°–30°	Asia Minor	11,000
30°–20°	Southern Himalaya	16,000
20°–10°	Colombia	15,000
10°– 0°	Venezuela	14,000
	EQUATOR	
0°–10° S.	New Guinea	14,000
10°–20°	Bolivia	16,000
20°–30°	Northern Argentina	15,000
30°–40°	Central Chile	5,000
40°–50°	South Central Chile	2,300
50°–60°	Straits of Magellan	1,600
60°–70°	Antarctica	At sea level

the snow line until the mountains of northern Labrador are reached, while beyond, in Baffin Land, the snow line descends to 2000 feet or less. In Europe the snow line is reached by the Pyrenees (6500 feet), the Caucasus (8500 to 14,000 feet), the Alps (8500 feet), and the Norwegian highland (3000 to 5000 feet). The Himalayas and other lofty mountains of central Asia rise above the snow line, as do the lofty mountain peaks of central eastern Africa at the equator. Next to Australia, which does not at any point rise above the snow line, Africa has the least area of snow field of all the continents. But while Australia does not rise above the snow line, New Zealand does.

Relation of Precipitation to Snow Line. — Since it is said that the snow line is determined by the excess of snowfall over melting and evaporation, it is evident that the amount of snowfall as well as the temperature must be an important factor in determining the snow line. This is well illustrated in the Alps, where the amount of snowfall on the southern side is greater than on the northern side, and in the Himalayas, where the same is true and the snow line therefore descends three or four thousand feet lower than the colder northern side. Many other mountains illustrate the same influence, as, for instance, the Alaskan mountains, where the snow line also descends greatly on the warmer ocean side, where the heaviest snowfall occurs.

Effect of Dry Air. — Since evaporation takes place from the surface of snow fields, there is more loss of snow on slopes exposed to dry winds than on slopes where the air is damper. Therefore the snow line is influenced to some extent by the dryness of the air, entirely apart from the fact that this condition causes less snowfall. It is partly for this reason that in Spitzbergen, although in latitude 78°, the snow line is not reached by some surfaces 2000 feet above sea level.

Relation of Snow Line to Exposure and Topography. — The position of the snow line is also much influenced by the exposure and topography. The nature of the slope of the surface, the effect of winds in sweeping off or in adding snow, exposure to the direct rays of the sun, protection from the sun by the shadows of cliffs or mountains, and the neighbourhood of ice to cool the air are among the factors that cause local variation in the snow line. Due to such influences, there may be a difference of 1000 to 1500 feet in the elevation of the snow line, even in a very short distance. The effect of the exposure and topography in the elevation of the snow line is well illustrated in Alaska and in Spitzbergen. In Ice Fiord in Spitzbergen, where the snowfall is light, there are some places in shaded spots, in which the snow is driven by the wind, where the snow line is but a few hundred feet above sea level, while near by no snow lies in summer at an elevation of 2000 feet.

The Nature of Snow Fields. — The snow surface that lies above the snow line is called the *snow field* (Fig. 118). Where the slopes are steep, as among many mountains, much of the snow is shed into the valleys, and an extensive part of the region above the snow line is bare of snow, while in the valleys it accumulates to depths of hundreds of feet. On the more gentle mountain slopes it may also attain great depths, especially in regions of heavy snowfall, like the coastal mountains of Alaska. The depth of snow, and the area covered, are also influenced by the relative proportion of snowfall to loss by melting, evaporation, and discharge through glaciers. The most favourable places for extensive snow fields are those of no great ruggedness, where loss from melting is slight or absent, and where slopes down which glaciers may flow are not steep. Such conditions are met in the Antarctic continent and in Greenland, where the most extensive snow fields of the present day are found. Other large snow fields exist in other Arctic islands; and there are extensive snow fields among the lofty mountains, notably in the Himalayas and in Alaska, where the temperature is low and the snowfall heavy.

Largest Snow Fields in Polar Regions. — Speaking generally, the snow fields become smaller from polar toward equatorial regions, because the area that rises above snow line diminishes in extent; and many snow fields in mountains of warm temperate or tropical latitudes are hardly more than large snow patches, preserved in protected spots. This statement is correct only in general, for where extensive areas of mountain rise well above snow line, and receive abundant snowfall, large snow fields may exist in the central temperate zone, as in the Alps and Caucasus, and even in the tropical zone, as in the Himalayas.

FIG. 118. — Snow fields near Yakutat Bay, Alaska. (Brabazon, Canadian Boundary Survey.)

Amount of Snow and Ice on the Earth. — It has been estimated by Chamberlin and Salisbury that there are, at present, on the earth not less than a million cubic miles of snow and ice, which, if all melted and returned to the sea, would cause a rise in the level of the ocean of about 30 feet.

Relation of Glacier to Snow Field

Amount of Snowfall. — The amount of snowfall in regions of existing glaciers is suggested by the annual precipitation of 187 to 671 inches of snow at Valdez, Alaska, and 300 to 400 inches at Field and Glacier, British Columbia. These are from places far below the snow line. High up in the snow fields of these mountain glaciers the precipitation is doubtless much greater. In Greenland and Antarctica a very much smaller snowfall nourishes the largest glaciers in the world, because the climate is so cold that much less, or perhaps none, of the snow is lost by melting and evaporation.

The Change from Snow to Ice. — As the snow fields accumulate, the lower portions slowly change to ice. The change of snow to ice is a familiar phenomenon during winter, when the melting of the surface snow furnishes water which percolates into the snow and freezes. The snow banks that are last to disappear in spring illustrate this clearly; and there is every gradation from the snowflake crystals to granular, icy snow, and to solid ice.

Doubtless this process operates also in the snow fields, for in parts of some of these there are periods of melting. But it is not the sole process by which snow is changed to ice, for this change occurs in regions such as central Greenland, where the melting point is never approached, even in summer. Experimentally snow can be transformed to ice under mere pressure, and the crystalline structure of the resulting ice is granular, as in glaciers. The exact process by which this change takes place is not yet demonstrated, but it seems to be a molecular rearrangement, as a result of which the molecules of the individual snowflake crystals join together to form larger crystals of compact ice. The air included between the snow crystals gathers in bubbles, scattered through the newly formed crystals.

The Beginning of Flowage. — When the snow field becomes thick enough, its lower portion is transformed to ice; and, upon attaining the requisite thickness, this ice commences to flow. The exact thickness required for the beginning of flowage is unknown, and it doubtless varies with the temperature of the ice and the slope on which it rests. A depth of several hundred feet is a minimum for ice flowage, but it is probable that in a cold region, like Spitzbergen, the requisite thickness is several times the minimum.

Relation to Pressure. — The flowage of ice is a direct result of the pressure, and the ice moves away from the pressure as a mass of wax will flow away from the pressure when a weight is placed upon it.

The flow of wax is the result of its viscosity, but it is not definitely known that ice is a viscous substance, though in large masses under pressure it flows much as viscous substances do. The exact physical processes by which the flowage is accomplished are not demonstrated. It may be actual viscous flowage, or it may be alternate melting and freezing at points and along planes under pressure, or it may be a molecular rearrangement under stress, or a movement along gliding planes, or a combination of two or more of these. The solution of this is a physical problem; to the physical geographer, the fact of prime importance is that the ice flows under pressure as a viscous substance does.

Zones of Fracture and Flowage. — During the transformation of snow to ice, and during the later motion, the ice develops a nodular crystalline structure, with crystals an inch or two or three inches in diameter. Ice is, therefore, a crystalline rock, one of the purest of rocks on the earth's surface. Like other solid rocks, it is brittle under ordinary atmospheric pressures, and may, therefore, be easily broken; but, under pressure of two or three hundred feet, strains and stresses no longer cause rupture, but give rise to flowage. Accordingly, a large mass of ice consists of an upper zone of fracture, and a lower zone of flowage, as the earth's crust does. From the behaviour of ice at the surface, therefore, one cannot draw accurate conclusions as to its behaviour under the pressure of several hundred feet of ice.

Flowing Ice Forms Glaciers. — Since ice under pressure flows, large snow fields, whose base is ice, contribute flowing ice. Such flowing ice is called a *glacier*. The size of the glacier varies with the extent of the contributing snow field. It may be small and short, or it may be many miles long, and many miles broad, according to the snow supply. Ordinarily the flow is down grade; but, where the pressure is sufficient, the ice may flow over level ground, or even up grade, if the pressure head be sufficient. Where the up-grade movement is extensive, the surface grade of the ice must be toward the direction of flowage, though the ground over which the ice flows may slope away from it; but locally ice may be forced up grade even without such an opposite ice surface slope.

Types of Glaciers

The Four Classes. — There is every gradation from snow fields to glaciers fed by snow fields, and from small, motionless ice masses to great glaciers. According to their size, origin, and position there are many differences among glaciers, and many names have been proposed for the different forms assumed. Among these, however, there are four types which have received quite general recognition: (1) *valley* glaciers, (2) *piedmont* glaciers, (3) *ice caps*, (4) *continental* glaciers.

Glaciers in Valleys. — Of these the simplest as well as the most common and best known is the *valley glacier*, which, as its name indicates, is a glacier in a valley, down which it flows. Since valley glaciers were first studied in the Alps, they are sometimes called *Alpine* glaciers. There are many differences in form and size of valley glaciers, according to the topography and the supply. They grade into mere snow fields where smallest, or stretch a score or two of miles along mountain valleys where largest, becoming great rivers of ice which deeply flood the valleys. The valley glaciers radiate outward from the mountain snow fields, from which they move the snow outward and downward to a warmer climate, where the ice disappears by melting.

Glaciers at the Bases of Mountains. — Where valley glaciers descend to the foot of a mountain and out upon an open slope, as into a broad valley or upon a plain, the glacier end spreads into an ice fan, or *bulb glacier*, or *piedmont bulb*. If two or more such bulbs coalesce, a broad-spreading glacier end is formed, to which the name *piedmont glacier* is applied. A piedmont glacier, therefore, has valley glacier feeders, but is itself a low-lying ice plateau, spreading with moderate flow over the low grade at the mountain base. The extent of its spreading will depend upon the amount of ice supplied, and the topography.

Small Ice Caps. — If the snow fields are extensive enough, and the loss by melting, evaporation, and ice drainage are not sufficient to prevent, they may completely submerge an area beneath a snow cap, which, since only the upper portion is snow while the lower portion is ice, is commonly called an *ice cap*. An ice cap most easily gathers upon a surface that is not very rugged, and, with especial ease, in a cold climate where melting is slight. Accordingly, ice caps are common in the Arctic regions, some of them being only a square mile or two in area, and with little or no motion, others covering very large areas, as in Vatna Jökull, Iceland.

Ice Sheets. — The ice cap merges imperceptibly into the *continental glacier*, which, in a sense, is only a large ice cap. Greenland and Antarctica contain the two largest existing continental glaciers, but during the Glacial Period continental glaciers also existed in northwestern Europe and northeastern North America. In the continental glacier there is a great ice cap, burying all the land, with the ice moving outward in all directions from the centre of accumulation, and, near its margin, being deflected by its valleys so as often to terminate in valley glacier tongues, or distributaries. The continental glacier is perhaps too large to be called a glacier, and it is sometimes referred to as an *ice sheet*. In its origin, nature of movement, and work performed, the ice sheet is, however, so like a glacier that, in spite of the size and other differences, it is properly to be classed as a great glacier.

VALLEY GLACIERS

ow Supply. — Glaciers really constitute a form of snow drainage; were it not for this leading away of the snowfall, the snow fields t accumulate indefinitely. In valley glaciers the process starts the snow itself, which not only falls directly from the sky into ys, but also slides into them from the steeper slopes. During r snow storm, and immediately after it, there is downsliding of reshly fallen snow, as there is from the steep roof of a house. at irregular intervals there are other, and often far greater, ınches of snow that has accumulated on slopes until it has become ıstable that it can no longer remain. Very often thousands of come crashing down the mountain slopes, and one of the dangers ountain climbing among the snow fields is from the snow slides ralanches, which, in lofty snow-covered mountains, often occur alarming frequency.

ded to this supply of snow is a not inconsiderable amount which wn into the valley by the winds which sweep over the snow fields. effect of these winds may often be seen where the snow has been t away from exposed places, or from around rock masses, as it m around boulders in a field. A considerable part of the blown collects in the more protected valleys, where it settles in the er air. In Spitzbergen there are many little glaciers or glacierets r the lee of cliffs. To these the wind sweeps the snow from the bouring hill or plateau tops, which in summer are free from snow, ugh higher than the glacierets.

us the valley glacier is supplied from (*a*) direct snowfall, (*b*) nching from the valley slopes, (*c*) by the indrift of wind-blown . The area in which these supplies are added is called the *glacier oir*.

e Wasting of Snow. — Naturally the reservoir extends down to ıow line; that is, to the line where snow supply and snow dissi-n are balanced. The glacier itself, flowing down grade, with a supply behind, can extend below the snow line into the zone where ıge exceeds snowfall. This is the zone of the *dissipator*. In the ator the wastage is primarily by melting, though there is also y evaporation. The term *ablation* is applied to the combined sses by which the glacier wastes.

was said that a glacier was a form of snow drainage, and that rst process in the drainage was movement of the snow itself. is continued by the motion of the ice in flowing down the valley, s completed by the melting of the ice in the dissipator and its ff in streams of water. Thus, snow that falls, even in the zone petual frost, at last finds escape to the sea, whence it originally as vapour.

ts of the Glacier. — The upper part of the glacier is the *snow* This grades into a zone of granular snow, called the *névé* or *firn*, and this, in turn, into the *ice stream*. These three zones are not definitely bounded, nor are they capable of exact definition. Ice may exist beneath parts of the snow field and the névé; and snow may rest upon the upper part of the ice stream. In general the snow field has little or no motion from flowage, the névé is slowly moving, and the ice stream moves only by flowage. The névé is the zone in which the snow becomes transformed to the crystalline ice. It may be entirely absent or invisible in large glaciers where the transformation occurs beneath great accumulations of snow.

Forms of Valley Glaciers. — Most commonly a valley glacier consists of a broad, branching supply ground, or reservoir, from which a tongue of ice protrudes down the valley to a greater or less distance. The surface slope is roughly accordant to that of the valley bottom, being somewhat steeper, and presenting the average slope, not the details. Large irregularities of the bottom may, however, be represented, as where domes of ice are raised in passing over buried rock hills, and where abrupt descents are represented by a roughly parallel descent of the glacier surface. At its front the glacier has normally a relatively rapid slope due to melting, and not at all related to the slope of the valley bottom.

Avalanches from steeply sloping Glaciers. — The slope of the valley glacier naturally varies greatly. Some have an average angle of slope of but a few degrees, and in walking up their surface one seems to be scarcely rising. Others are so steeply inclined that it seems a wonder that they are able to maintain themselves. Indeed, such glaciers do occasionally slide out of their valleys. In the spring of 1901, for example, such a fall occurred in the Alps, and the avalanche to which it gave rise swept across the road over the Simplon Pass, burying a village and killing most of the inhabitants. A similar glacier fall occurred in Yakutat Bay, Alaska, in 1905, sliding out of a steeply perched valley and the ice falling over 1000 feet into the fiord. Since there were no inhabitants here, there was no destruction of life or property; but a huge water wave was generated in the fiord, which swept the neighbouring coast to a height of 110 feet; and fifteen miles away, where the author observed its effects, to a height of 15 or 20 feet.

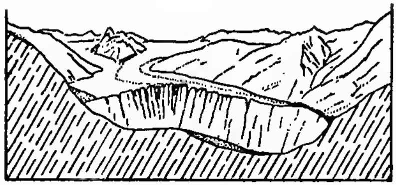


FIG. 119. — Cross-section of a valley glacier. (Shaler and Davis.)

Cross-section of Ice Tongues. — In cross-section the surface may be fairly flat in large glaciers well above the snow line, and there may even be a rise at the sides, where snow has slid from the mountain slopes. Here the glacier crowds up to the mountain side, and its surface plane is in contact with it.

Farther down, and especially in the dissipator, the form more commonly considered typical of glaciers is found. This is a gentle rise toward the centre from each side, and a fairly sharp descent as each mountain wall is approached, forming a marginal valley with the glacier for one wall and the mountain side for the other. This valley is due to melting, for the rate of melting is increased along the glacier margin by the warming of the mountain surface in the sun. A valley may not develop in places where the rate of ice movement is sufficient to crowd the ice against the valley side; and the rate needed to bring this about need not be so great in the shady as on the sunny side. Toward the end of the glaciers, where melting is most rapid, ice thickness least, and motion slowest, the marginal valley

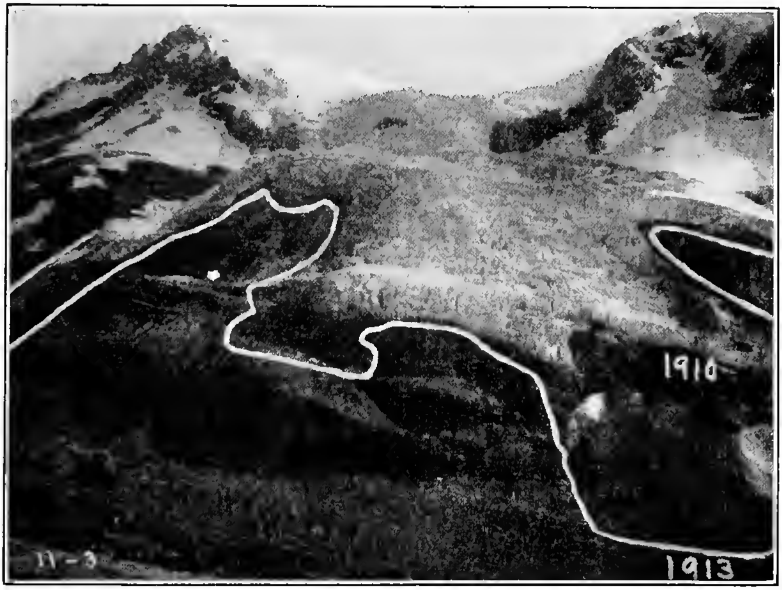


FIG. 120.—Cascading Glacier, Alaska, descending out of a high mountain valley. It receded from 1905 to 1910, but advanced between 1910 and 1913.

becomes best developed. This broadening of the lateral valleys, together with more rapid motion in the centre, causes the lobate terminus characteristic of glacier ends on the land.

Other Kinds of Glaciers. — Besides valley glaciers with the characteristics mentioned, there are many variations from this, which may be thought of as typical or normal. There are, for example, glaciers on ledges of various shapes on the face of the cliff, called *cliff* or *cornice glaciers*. Some are circular, or semicircular, or linear, or irregular. Other glaciers terminate on the face of a cliff, in a broken end, like a frozen cascade (Fig. 120), and known as *cascading glaciers*.

Ice blocks discharged from the terminus of a glacier ending on a cliff may accumulate below and, becoming recemented, form a new ice mass called a *recemented* or *reconstructed glacier*. Other glaciers, instead of rising to a well-developed, broad snow field, may

FIG. 121.—A through glacier (on right) between Nunatak Fiord and the Alsek River, Alaska; medial moraines (on left).

head on a low, flat divide from which another glacier descends in the opposite direction. Such a glacier, which is double-ended, and continues from end to end, is a *through glacier* (Fig. 121). In Alaska there are high level, glacier-like masses whose termini and even whole extent are buried beneath angular débris. For these the name *rock glaciers* has been proposed, but the author's interpretation is that

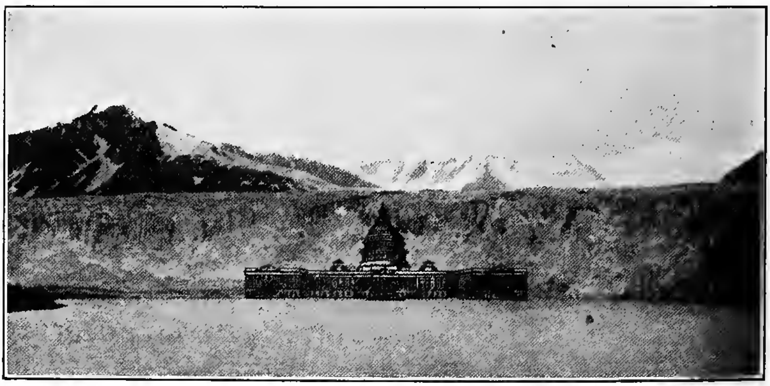


FIG. 122.—Part of terminus of Childs Glacier, Alaska, compared in height with the Capitol in Washington, which is $287\frac{1}{2}$ feet high.

these represent a phase of moraine-covered glacier, preserved and modified by the presence of perpetual frost in the moraine. These are some of the subtypes of valley glaciers, which will serve to indicate that there are variations from the class described as normal.

Size of Valley Glaciers. — In the Alps, where there are a great many glaciers, there is every gradation from glaciers a few hundred feet long to the great Aletsch which is 10 miles long, or, with its snow field, fifteen miles. The average length of the better-known glaciers of the Alps is from 3 to 5 miles; but the majority of the Alpine glaciers are less than a mile in length. The Aletsch is about a mile wide, but most of the glaciers of the Alps are much narrower.

FIG. 123. — Three of the largest Swiss glaciers (in black) compared in size with the Hubbard Glacier in Alaska.

Far larger valley glaciers are formed in the Caucasus, Himalayas, southern Andes, and the mountains of the Alaskan coast. Here glaciers 20 to 40 or even more than 50 miles in length are found; and widths of from 3 to 5 miles are not uncommon. The Muir glacier of Alaska, for instance, is about 35 miles long and from 6 to 10 miles wide, the total area of the ice surface being about 350 square miles. Other large valley glaciers in Alaska are the Hubbard, Seward, Miles, and Columbia (Figs. 122, 123, 125, 126).

Tidal Glaciers. — The smaller glaciers terminate only slightly below the snow line, but the larger ones may descend far below it. The

FIG. 124. — An iceberg stranded at low tide. The portion below the dotted line is submerged when the iceberg floats.

Aletsch, for instance, terminates at an elevation of 4440 feet, which is about 4000 feet below the snow line. The great majority of valley glaciers terminate on the land, but some of the larger ones, in regions where the snow line is low, push on to sea level, and there discharge

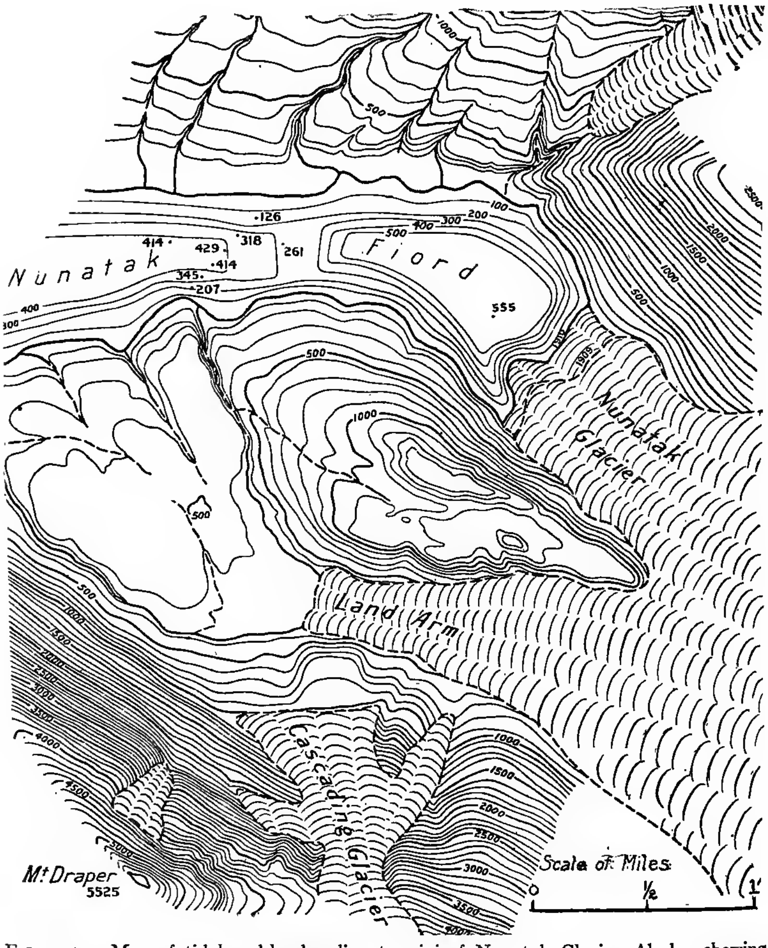


FIG. 125.— Map of tidal and land-ending termini of Nunatak Glacier, Alaska, showing advance from 1909 to 1910, submarine topography of Nunatak Fiord, and two cascading glaciers in hanging valleys.

their ice into the sea as icebergs. This is true of the Muir, Taku, Hubbard, Columbia, and other Alaskan glaciers. Glaciers terminating in the sea are called *tidal glaciers* (Figs. 125, 126, 130, 132).

Thickness of Ice Streams. — Little is known with regard to the thickness of glaciers. It is estimated that the Alpine glaciers attain a depth of from 800 to 1200 feet, and the fronts of tidal glaciers, below as well as above sea level, are sometimes 900 to 1000 feet high. It is probable that the great ice streams like the Muir, which is 900 feet thick at the end, are much thicker than the Alpine glaciers. The Grand Pacific Glacier, near the Muir, is known to have been over 2500 feet thick in 1894 at a point about twelve miles from the terminus.

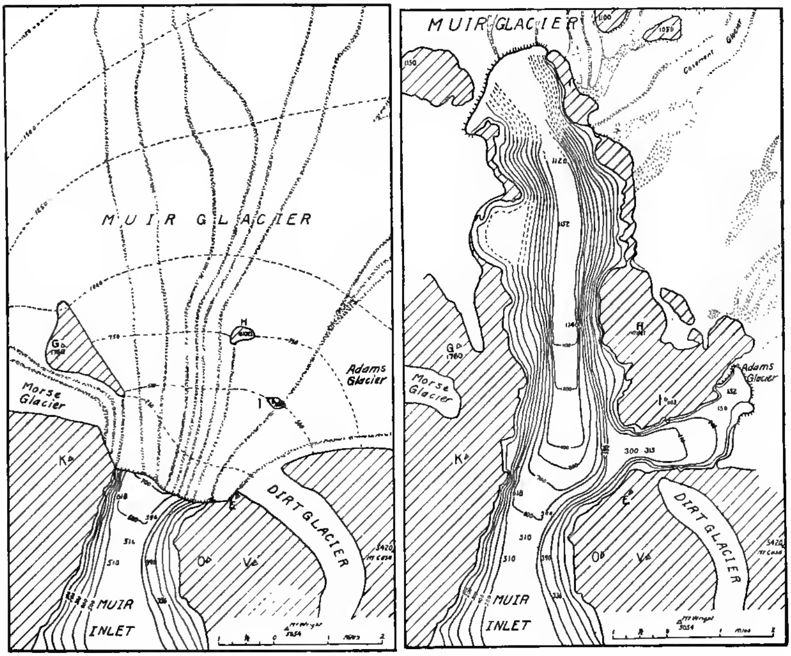


FIG. 126. — Muir Glacier in 1892 and in 1913. In 1892 the ice stream was nearly 2400 feet thick 6½ miles from the terminus. (Left-hand map after Reid.)

It is probable that some Alaskan glaciers reach depths in excess of 3000 feet; yet, since ice will move more rapidly with increased pressure, the thicker the glacier, the greater tendency there is for the ice to flow down the valley, and hence to put a check upon the depth.

The glacier depth is normally greatest in the middle, partly because the ice surface is often highest there, and partly because the valley depth is greatest there. At the margins the ice may thin to a depth of but a few feet. The forms of the cross-section will vary greatly, according to the form of the valley into which the glacier is moulded. Its lower surface has the curve of the valley bottom, but its upper surface is variable. It may be a straight line, though usually it is gently curved upward toward the middle; and in the zone of the dissipator it curves sharply downward near the margins (Fig. 119).

Rate of Motion. — There is much difference in the rate of motion of valley glaciers. Some of the smallest are almost, if not quite, motionless, while large glaciers move at the rate of several feet a day. The rate of motion in a glacier increases from the margin toward the center (Fig. 127). Thus in the Mer de Glace, in Switzerland, the daily rate of motion in summer and autumn was from 13 to 19½ inches near the sides, and much less at the margins, while in the center it was from 20 to 27 inches. This is one of the most rapidly moving, as it is one of the largest, Swiss glaciers. Reid found that

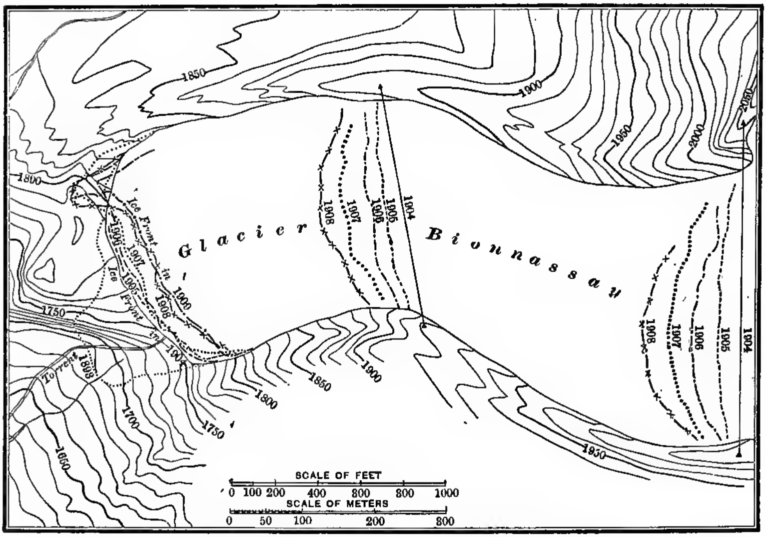


FIG. 127.— Glacier in the French Alps, showing more rapid motion near center than at sides. Elevations in meters. (Mougin, Ministère de l'Agriculture de France.)

the Muir Glacier, near its end, was almost if not quite motionless at the sides, but rapidly increased in rate toward the center, where its motion was 7 feet a day. While this is rapid motion for a glacier, it is probable that some of the larger glaciers move even faster; and some of the tongues extending to the sea from the Greenland ice sheet flow at a rate of 60 to 75 feet a day. Childs Glacier in Alaska moved at the rate of 8 to 40 feet a day in 1910 (Fig. 128), but in the previous year it was moving at the rate of only 4 to 6 feet a day.

It is impossible to obtain accurate measurements of rate of flow of a glacier from top to bottom, but there is reason to believe that the basal layers are retarded by friction. · Measurements made by Tyndall near the side of a glacier showed a decrease in movement downward. It cannot be said, however, that the exact nature of the change in rate in the glacier as a whole is definitely determined by this observation.

The rate of motion varies with the supply, being greatest in those glaciers which have large supply. It also varies with the slope, though it is not true that the steepest glaciers flow fastest, because steep valleys are apt to be small and with small ice supply, while many large valleys, with moderate slope, have so large a supply that there is rapid ice flow.

There is also a variation with the temperature, for the ice flows fastest when near the freezing point. Thus the glacier is thought by some to move faster in summer than in winter. The variation from side to centre, mentioned above, is due to the influence of friction, and

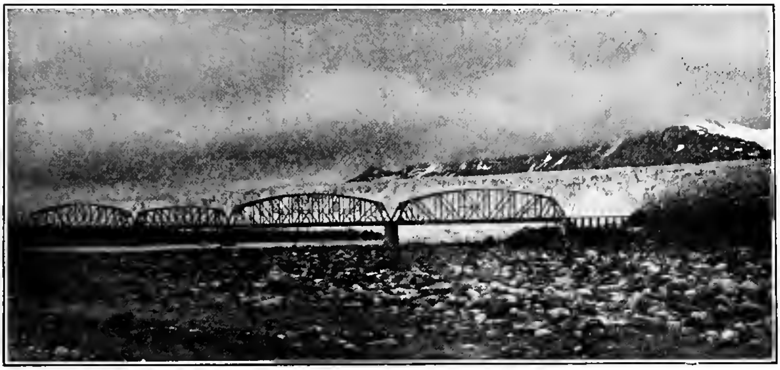


Fig. 128. — Railway bridge over Copper River, Alaska, costing $1,400,000, which was threatened by the advance of Childs Glacier in 1910.

to the thinness at the edge. Since friction retards motion, the nature of the valley floor has influence on the rate of motion, as irregularities in the bed of a stream have on the flow of the water. Still another influence on rate of flow is the presence of débris in the ice. When heavily charged with rock fragments flowage is retarded.

Advance and Recession. — The position of the end of a glacier is determined by the balance between supply and wastage. It can rarely happen that so delicate a balance will be able to maintain an ice front at a given point for a long period of time, for, with climatic change from year to year, the supply may vary, or the rate of ablation may vary. This gives rise to fluctuations in the ice front, some of them minute and seasonal, some of notable extent.

Cycles of Advance and Recession. — At the present time there seems to be a general condition of wastage, and ice fronts are, in the main, in recession. This has been true in the Alps, Pyrenees, and

Caucasus for several decades, though prior to 1855 there were advances. The Alaskan glaciers, and those of other regions, are, in general, thought to be in recession. There are reasons for believing it probable that there are cycles of advance and recession, due, perhaps, to climatic variations; and careful records are now being kept in the hope of discovering the cause for variations in the position of glacier fronts.

Advance interrupting Recession. — Even during periods of general recession individual glaciers may advance, as the Vernagtferner in the

FIG. 129. — Views of Hidden Glacier, Alaska, from the same point before and after a two-mile advance. At *B* the ice was 1100 feet thick after the advance.

Austrian Tyrol has done, and as the Yakutat Bay glaciers have since 1901. In the latter case the advance has been due to the avalanching of great masses of snow into the glacier reservoirs during the vigorous earthquakes of 1899. This spasmodic and great addition to the supply has started a wave of advance which, sweeping rapidly down the glacier, has pushed forward the fronts of glaciers that were hitherto receding. In one case a glacier front, the Hidden Glacier, was pushed forward two miles in a brief interval of time. Another advanced a mile in nine or ten months, which is at a rate of not less than 20 feet a day (Fig. 129).

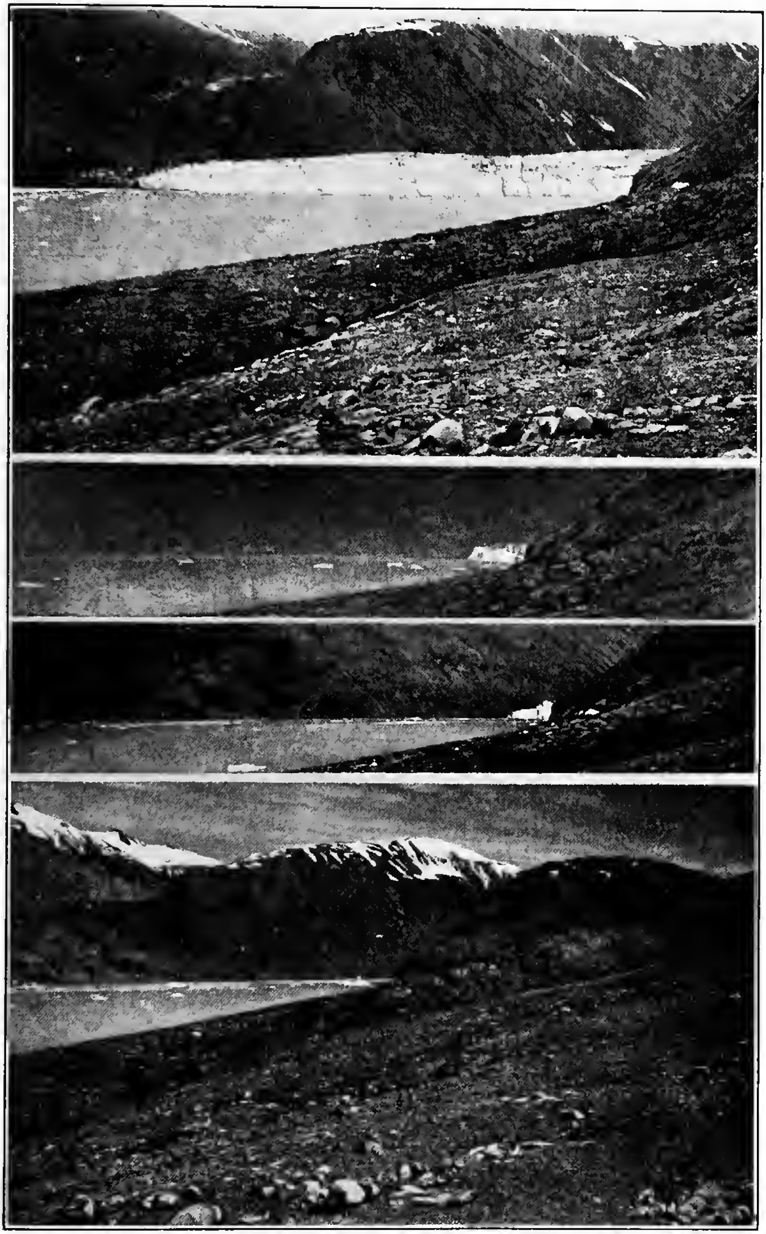


FIG. 130. — The receding Nunatak Glacier in 1899, 1905, 1906, and 1910. (Upper view by Gilbert.)

Rates of Recession. — When glaciers whose ends are on the land are receding, the rate is less rapid, for the recession can go no faster than ablation removes the ice. Before its advance the Hidden Glacier was receding at the rate of between one-half and one foot a day as an average for 6 years. This rate is much more rapid than that of the recession of the glaciers of the Alps. A tidal glacier may recede even much faster when the supply diminishes, for the discharge of ice in the form of icebergs is more rapid than that through melting alone. Thus Nunatak Glacier, in Alaska, had an average daily recession during 6 years, between 1899 and 1905, of about $2\frac{1}{2}$ feet; Muir Glacier, between 1892 and 1913, receded at an average rate of over $5\frac{1}{3}$ feet a day, and Grand Pacific Glacier for two months in the summer of 1912 receded at the rate of 80 to 120 feet a day (Figs. 126, 130).

Ice Structure. — As has been stated, glacier ice is coarsely crystalline. The ice is not uniform throughout, but is veined and stratified. Some of the differences are due to the size of crystals, some to the presence or absence of included air bubbles, and some to layers of included débris. Very often layers or veins of clear, transparent ice reflect a blue color and are called blue veins, forming a striking contrast to the opaque, whitish ice.

The cause for the veining of glacier ice is not perfectly understood, and it is probable that the cause is different from glacier to glacier and from place to place in the same glacier. Among the causes for veining are (*a*) freezing in cracks which have been filled with water; (*b*) stratification in the snow fields; (*c*) differential motion and shearing, due to the fact that ice moves at different rates in its different parts. The bands and veins of different kinds of ice are often greatly contorted, as layers of metamorphic rocks are, showing that, after formation, they have been subjected to plastic motion. They lie at all angles in glaciers, from horizontal to vertical.

Surface Features. — The surface of a valley glacier is a snow-covered waste above the snow line; but in the zone of the dissipator it assumes greater variety. Here the veined structure is revealed, there is a greater or less burden of rock material, and the surface is broken more or less by fissures or cracks. In summer an ice surface itself is granular and crumbles, for ablation has weathered out the crystal grains so that they adhere loosely, if at all. Immediately beneath, however, is massive ice, though water is sinking into this ice in the pores and between the crystal faces.

Moulins and Surface Melting. — As the ice melts there are innumerable tiny streamlets, which, uniting, sometimes give rise to small, short streams; but these soon find escape through a hole in the ice, a *moulin*, which the running water may enlarge so as to form a large pit in the bottom of a roughly circular area — resembling a sink hole of a limestone country. The water that falls into the moulin may cascade to the glacier bottom, or may find escape along a channel in the ice. Beneath the ice it may excavate pot holes in the rock, me of which are called giant kettles or cauldrons. Such pot holes ay be seen at Lucerne. Near the front and margins innumerable reamlets run down the steep ice slopes to the bordering land. uring the summer days the ice surface may waste from 1 to 4 ches a day.

Glacier Wells and Rock Tables. — The presence of rock fragments . the glacier surface often clearly shows that ablation is rapid. If a agment is small enough to be warmed through on exposure to the n, it will melt its way into the ice; and it is not uncommonly the se that the ice surface is pitted by little circular wells, at the bottoms which lie small stones or a thin layer of sand or mud. On the other nd, if the fragment is too large to be warmed through, it protects

:. 131. — Crevasses in Seward Glacier near Mt. St. Elias, Alaska. (Ogilvie, International Boundary Survey.)

e ice beneath from melting. Then as the ice surface melts down, is part is left standing with a rock cap, forming a *glacier table*. As e ice pedestal melts the stone slides off, leaving an ice pyramid, iich then slowly melts away. A similar change takes place when id or mud accumulates in a depression to a sufficient depth to pro- :t the ice. Then, with further melting, a sand or mud-covered ramid or ridge is left, from which the loose material is later washed ay.

Crevasses. — One of the most striking features of a glacier surface the *crevasse*, a yawning fissure extending down into the ice. The :vasse is due to a straining of the ice to the rupture point. It rts as a mere crack, then is widened by further pulling apart and melting. If we think of the ice as a plastic mass with a brittle or igid crust, it is easy to see that, as the under ice flows, the rigid ice it is borne along by it will be ruptured when subjected to straining.

It is also easy to see that there will be a limiting depth for the crevassing, for it cannot extend into the plastic ice below. Crevasses are but 200 or 300 feet deep, and commonly less (Figs. 131, 132).

The abundance of crevasses varies with the amount and rate of the straining. In rapidly flowing glaciers, even on a regular bed, there is great crevassing, and the glacier may be so broken as to be impassable from one side to the other. By melting, the surface becomes transformed to a maze of ridges, pinnacles, and seracs, with intervening yawning crevasses. A similar condition appears where a glacier flows over a sharp incline in the valley bed, giving rise to what is called an *ice fall* or an *ice cascade.* Such ice falls interpose serious obstacles to travel over a glacier surface. Below the ice cascade the crevasses may be closed again, or, if not, their bottoms are soon reached by the general lowering of the surface through ablation.

Crevasses also develop through the strain introduced by differential motion, and individual crevasses may appear in any part of the glacier. There is often a zone of crevassing extending from the sides out toward the center of the glacier as a result of the more rapid rate of motion in the center. This exerts a strain at an angle with the direction of motion of the glacier, and the ice is pulled apart by the tension, giving rise to fissures at right angles to the strain. Thus these crevasses point up the glacier at an angle of about 45° to the direction of motion. These fissures are sometimes developed in such numbers as seriously to interfere with passage over the glacier surface.

Any tension sufficient to rupture brittle surface ice may develop crevasses. Such strains may be set up either by differential motion of the flowing lower ice, or by topographic influence of the slope and motion of the rigid upper ice. Under the multitude of conditions of movement and topography affecting glaciers there are innumerable detailed causes for crevassing. A glacier that is stagnant and uncrevassed may, upon being forced to move, become greatly crevassed, as the advancing Yakutat Bay glaciers were. The thrust may even cause horizontal or thrust faulting in the ice, and the rigid margin of an advancing glacier may be broken into fragments, which, with the continuation of the push, fall from the sides as detached ice blocks. This is one of the causes for the discharge of icebergs from the face of a tidal glacier.

Crevasses are not confined to the lower portion of the glacier. They occur also in the névé and on the glacier above the snow line. In such positions the snow often partly or completely covers them and hides them from view. This is one of the dangers which mountaineers must guard against when travelling above the snow line.

Transportation of Rock Material. — Rock fragments are supplied to glaciers for transportation in several ways. Some is blown in by the wind, and still more falls from the valley sides, where the rock fragments are loosened by weathering. Far greater quantities come with the snow in avalanches. Thus rock fragments, of varying size,

FIG. 132. — Crevassed tidal terminus of Nunatak Glacier, Alaska.

are scattered through the ice of a valley glacier, the quantity varying according to conditions. To this supply of rock fragments the glacier adds still more, which it picks up itself from its bed. Some of these

FIG. 133. — Débris-laden basal ice of Hubbard Glacier, Alaska. Such ice is especially effective in glacial erosion.

fragments are plucked loose by the powerful thrust of the ice, and some are ground off by the scouring of the valley bottom as the moving ice drags rock fragments over it. When on or near the surface of a glacier, they are prevailingly angular.

Unlike the other agents of transportation ice carries rock fragments irrespective of size. A boulder tons in weight may be transported side by side with a grain of sand or clay. There is no such assortment according to size and specific gravity as is a necessary result of transportation by wind and running water.

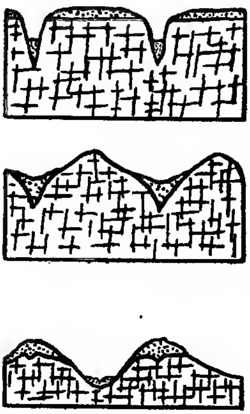


FIG. 134. — Three stages in the appearance of débris-covered ice. (Gilbert.)

The Supply of Débris. — Owing to the nature of the source of the rock fragments, the débris in a valley glacier is carried mainly (*a*) near the bottom, (*b*) at or near the top, though there is (*c*) some rock material between the top and bottom incorporated in the ice when it was formed out of the snow. The débris at the surface is especially abundant because it settles there from the air and falls from the cliffs. It cannot sink to the base of the ice, and that which falls into crevasses goes but a short distance into the ice, and is soon exposed at the surface again when ablation lowers the surface to the crevasse bottoms. Ablation also concentrates the incorporated débris of the upper glacier at the surface by removing the ice from it.

The Débris-laden Basal Ice. — The bottom is a zone of abundant débris, because the ice is there busily at work eroding its bed and moving the loosened fragments away. Most of this débris remains at

FIG. 135. — Surface of Valdez Glacier, Alaska, completely covered with ablation moraine.

FIG. 136. — Shrubs growing in ablation moraine on Grinnell Glacier, Alaska.

or near the bottom, because there are no such uprising currents as in rivers. Yet there is some uprising, and bottom débris is, therefore, brought up into the ice, especially near the front and the margins (Fig. 133).

The Débris-covered Terminus. — Above the snow line little débris is seen on the glacier surface, for it is buried by the snowfall. In the dissipator, however, it is brought into view and often into relief. Rock fragments are scattered all over the surface, but are especially abundant near the margins where they have fallen from the enclosing cliffs. The protection given by these zones of rock fragments causes them to form ridges which seem to be ridges of débris, but are really ice ridges, thinly veneered with a protecting coat of débris (Fig. 134).

Moraines on the Ice. — The débris carried by a glacier is called *moraine.* The bands near the margins of the glacier are *lateral moraines.* They are supplied chiefly by mechanically weathered material which falls from the valley walls, but some of the material in lateral moraines is supplied by the uprising of ice layers near the margins of the glacier.

Bands of *medial moraines* (Fig. 121) often extend down the central part of a valley glacier, some of them representing the lateral moraines

Fig. 137. — Glacial boulders, the one on the left from till deposit in central New York, the one on the right from the Greenland ice sheet.

of tributary or uniting glaciers. Sometimes there are several ribbons of medial moraines, each marking the incoming of a branch higher up. Other medial moraines come from buried rock knobs, being exposed at the surface farther down the glacier by ablation.

In some cases, as in Alaska, so much débris is incorporated in the glacier that ablation concentrates it in a uniform sheet, completely hiding the surface of the ice with a coat of *ablation moraine* (Figs. 135, 136).

Moraine Deposited by Melting Ice. — The rock fragments in the base of the glacier constitute the *ground moraine.* As the glacier moves forward to its front, where it terminates by melting, it brings up to the front a large part of the moraine load, though some is removed by the running water of the melting ice before it reaches the front. The ice at the front melts and flows away as running water, but it can carry with it only a part of the rock load that the ice bears. This falls to the base of the glaciers, and there builds up a deposit, called the *terminal moraine*. If the ice front remains in approximately one position for a long enough period, a very considerable deposit may be made. Terminal moraines of some extinct glaciers of large size in the Alpine valleys are two or three hundred feet high.

Deposits by Valley Glaciers. — Being an agent of erosion and transportation, glaciers are necessarily also agents of deposition. Since the ice is ultimately transformed to water, both ice and water are

FIG. 138. — Terminal moraine of Columbia Glacier, Alaska, where advance in 1910 resulted in the formation of a push moraine of till, peat, and vegetation.

involved in the deposition of glacier-borne débris. Those accumulations made by the ice are *glacial deposits;* those made by the glacier-supplied waters are called *glacio-fluviatile deposits*. The term *glacial drift* is often applied to these ice and ice-born-river deposits.

Boulder Clay or Till. — The deposits made directly by the ice are characterized by their heterogeneous nature. Both large and small fragments occur side by side in the same deposit, with little or no assortment. There is, therefore, an absence of stratification, though there may be a rough lamination due to the effects of ice motion. Owing to the fact that the glacier glides along its bed, there is much clay, and the deposit is often called *boulder clay*, indicating that the matrix is clay, set with boulders, some of which are of large size. Another name, more commonly used, is *till.*

Shapes of Glacial Boulders. — The shapes of the stones in the boulder clay are distinctive. Though prevailingly angular when supplied to the ice, they are abraded into faceted, or soled, subangular form (Fig. 137). They usually bear glacial scratches or *striæ.* Indeed they are so different from stream-worn or sand-blasted stones that they may be distinguished at a glance, even in the consolidated and indurated glacial till of past ages. Such glacier-derived shales made from boulder clay or till are called *tillite,* and are usually identified by the presence of subangular, striated, glacial boulders.

Ground Moraine. — When a glacier has abandoned a valley, the till occur in a sheet spread over the region occupied by the glacier,

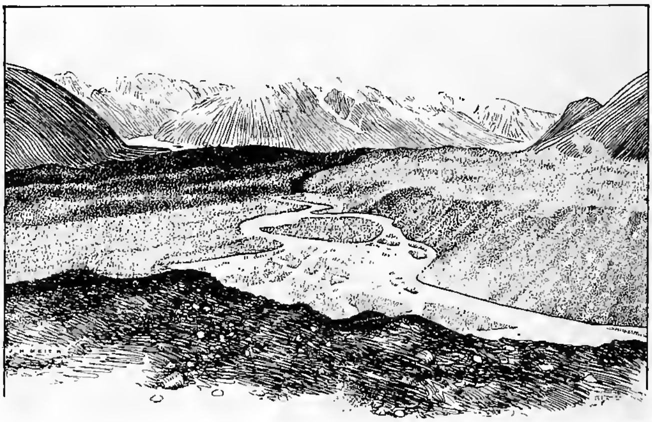


FIG. 139. — Glacial streams depositing gravel and sand in the interior flat of Variegated Glacier, Alaska. If the moraine-covered ice should now melt away there would be an oval area of stratified gravels completely surrounded by unstratified till.

having been left there when the ice melted. The till sheets represent that part of the moraine in and under the ice that was not carried away by streams when the ice melted. It is sometimes called the *ground moraine,* and in regions occupied by valley glaciers is not commonly very thick. It may, in fact, fail to even veneer the bed rock, and may be represented primarily by boulders and little pockets in depressions, the rest having been carried away when the ice melted or by later erosion.

Terminal Moraine. — The medial and lateral moraines, also lowered to the valley bottom, occasionally form prominent lines of moraine, composed of angular fragments among which are many boulders. There are also *terminal moraines,* marking the sites of halts in the receding ice. These moraines are formed partly by the falling of fragments from the ice front, partly by the dragging forward of débris beneath the thin ice terminus, though, judging from conditions in living glaciers, the latter is a less effective cause for terminal moraines than the former (Fig. 138).

Lateral Moraine. — The process of dragging beneath the ice by lateral shove may also help to accentuate *lateral moraine* deposits, which are often very pronounced in valleys formerly occupied by glaciers. Running water is another factor at work in the deposit of both terminal and lateral moraines, so that they are often complex both in form and in composition.

Glacio-fluviatile Deposits. — There is some lateral drainage in the valley between the glacier and the mountains, and here complex marginal deposits are made, which may later be interpreted as lateral moraines. There is also drainage beneath the ice, for the multitude

Fig. 140. — An Alaskan glacier which readvanced and covered its earlier gravel deposits. When it melts, a superposition of till upon stratified drift will be found.

of rills on the glacier surface, descending through moulins, forms a subglacial drainage of importance. This drainage emerges from near the center of small valley glaciers, and from near the margins of larger glaciers, often flowing as violent torrents, heavily laden with sediment. Their volume, which is greatest in summer, and increases with the daytime melting, is easily seen to be the result of melting of the glacier, though some may be contributed from land streams descending the mountain slopes (Figs. 80, 139, 140).

Rock Flour. — The sediment load is given to the water as the ice melts and loosens rock fragments which it is carrying. A large part of the sediment is derived from the basal layers, where there is much finely ground rock, called *rock flour.* The streams bear so much of this rock flour that they are clouded with it, and retain a portion of the fine sediment even when standing for a time. The streams issuing from most valley glaciers are so milky in colour from the quantity of finely ground rock flour in suspension, that their water has been called *glacier milk.* In some regions, where the rocks have a strong colour, or the load is excessive, the glacial streams are discoloured brown, or other colour.

The Reason for Deposition. — The glacial streams are at times such torrents that they bring from their ice caves, or tunnels, stones and even small boulders, as well as rock flour and sand. As the torrents rush these materials along, rapidly rounding them by attrition, one can hear them bumping together as they roll along the stream bed. When confined within an ice tunnel, and under a head of water from up the glacier, the glacial streams can bring out of the ice a volume of sediment which cannot be transported down the slopes of the valley. Consequently, deposit quickly commences, and an alluvial fan is started with the apex at the ice tunnel. Over

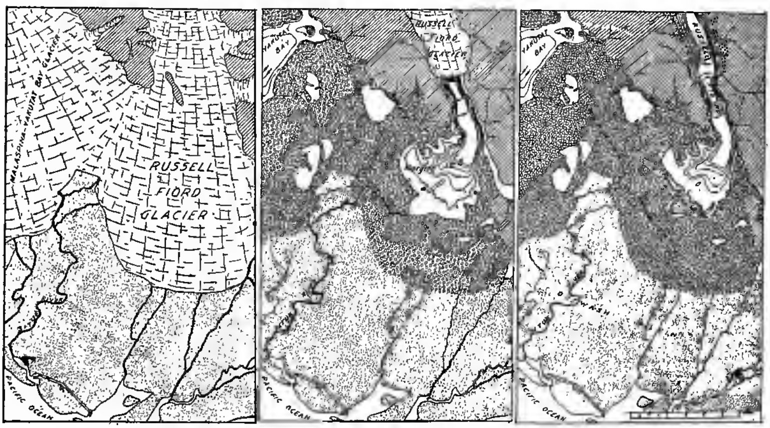


Fig. 141. — Relations of outwash gravels (stippled), terminal moraine (circles), lake deposits (horizontal lines), and overridden gravels (large dots), to three stages in glaciation of Russell Fiord, Alaska.

this fan the stream spreads in a multitude of distributaries which with their smaller volume are the seats of still more deposit (Figs. 80, 141).

Outwash Gravel Plains. — Such a deposit, called an *outwash gravel plain*, or *valley train*, may spread over the valley bottom from side to side and accumulate to a depth of scores of feet. It is stratified, and the gravel is coarsest near the glacier, where the stones may be a foot or two in diameter, and it may grade down to a sand plain. Ordinarily, however, it is a gravel plain with well-rounded stones, and crossed by numerous channelways. Very often the alluvial fan grows upward over the terminus of the glacier, burying the ice, especially where it has reached a state of stagnation. Later melting of the buried ice gives rise to pits, hollows, and kettle-shaped depressions

FIG. 142. — Kettles in pitted valley train of Hidden Glacier, Alaska, in 1905.

in the outwash gravel plain. Such a feature is called a *pitted plain* (Fig. 142).

Marginal Lakes and their Deposits. — At the margins of valley and piedmont glaciers small lakes are sometimes held in between the ice and the land (Fig. 143), like the Berg Lakes of Bering Glacier in Alaska (Pl. IV), those at the borders of Malaspina Glacier near the Chaix Hills, and the Märgelen See of Aletsch Glacier in Switzerland. They often drain out over adjacent cols or else beneath the ice, in the latter case causing destructive floods. In these marginal lakes the streams from the glacier deposit sediment, and when the glacier melts and the lake disappears, these form deposits of *lake clay*.

These are some of the principal glacio-fluviatile deposits connected with valley glaciers; but there are other forms, whose description is taken up among the deposits of continental glaciers.

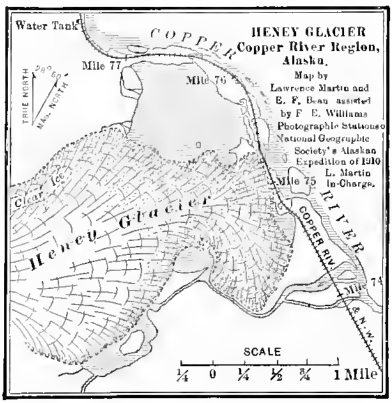


FIG. 143. — Marginal lakes between an Alaskan glacier and its terminal moraine.

Erosion by Valley Glaciers. — Valleys that have been occupied by glaciers show many signs of powerful glacial erosion. Many of the pebbles and boulders that were left by the glacier are polished and striated by the attrition to which they have been subjected as they have been ground against one another or against the valley bed. The rocks of the valley floor and sides are likewise polished, striated, and grooved (Fig. 144). It is as if a great sandpaper, studded with large rock fragments, and pressed heavily down on the valley bottom, had

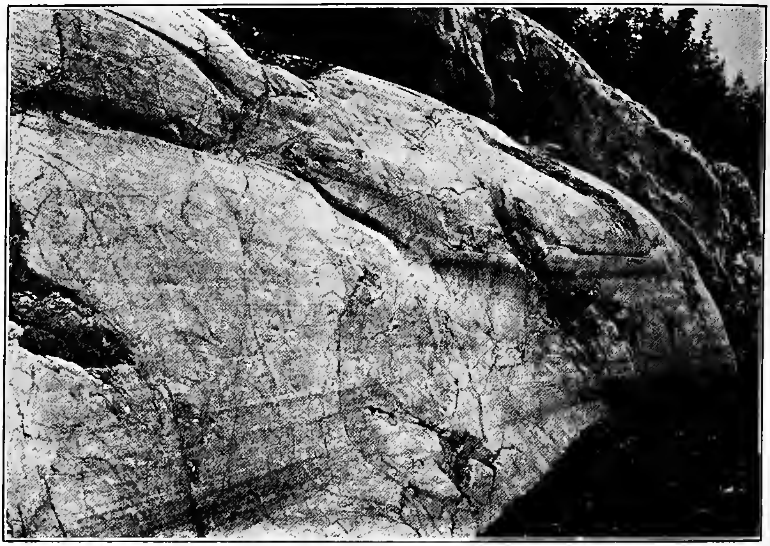


FIG. 144. — Glacial striæ and grooves on a valley side in Alaska.

been dragged over it. Here and there, too, are places where the blocks of rock have been torn off bodily or *plucked* (Fig. 145). Irregularities of the rock floor are smoothed and rounded into swinging curves, and dome-shaped bosses, known as *roches moutonnées* or sheep backs. Because of the steepness and plucked character of the lee slope, they look rough from that side, but the name was given on the basis of their smooth appearance as seen from the abraded side (Fig. 146).

These features are so characteristic that one can tell of the presence of former glaciers from such signs alone. Coupled with this is the fact that streams from the glaciers are burdened with rock flour and partly ground-up rock, while the lower layers of the glacier are charged with rock fragments. These phenomena make it clear that glaciers are eroding their beds, though at what rate cannot yet be told. Yet, though the rate be ever so slight, if it proceeds through long

FIG. 145. — Rock surface in California made irregular by glacial plucking. (Gilbert, U. S. Geol. Survey.)

FIG. 146. — Roche moutonnées in the Sierra Nevada. (Gilbert, U. S. Geol. Survey.)

enough time, it will be competent to notably deepen and broaden the valley, as the slow work of rivers and weathering can.

Characteristics of Ice-sculptured Valleys. — There are clear and conclusive evidences that time has not been lacking, for there are features characteristic of glaciated regions that admit of no other explanation than that of profound deepening and broadening of valleys by glacial erosion. Of these features one is the U-shape of the glaciated valleys (Fig. 147) where the sides are steep, as in young valleys, but the valley bottom is broad and more like that of maturity. No known process of river work will produce such a

Fig. 147. — U-shaped valley in Alaska.

valley. The projecting and overlapping spurs that characterize steep-sided valleys in the stage of youth are truncated, and in some cases even erased, by the powerful erosion of the glacier (Fig. 149). Some of these glaciated valleys are so straight that in Alaska they have been called *canals* (Fig. 154).

Hanging Valleys. — In valleys with these peculiarities there is a peculiar relation between tributary and main valleys. A normal stream valley system has its tributaries entering the main valleys at or near the level of the main stream (p. 177); but in glaciated valleys many of the tributaries enter the main valley hundreds, or even a thousand feet or more, above the main valley bottom. Such a valley is called a *hanging valley*. In it a stream flows with a certain slope, then, reaching the lip of the hanging valley, finds an abrupt change

FIG. 148.—Head of an ice-sculptured valley in the Alps with much bare rock and small rock basin lakes. Grimsel Pass, Switzerland.

FIG. 149.—Oversteepened side of a glaciated Alpine valley without overlapping spurs. Lauterbrunnen Fall.

in slope down which it leaps in a single fall or in a series of cascades to the main valley bottom. It is a wholly inexplicable phenomenon on any theory of river erosion, but finds ready explanation under the theory of glacial erosion (Figs. 150, 151).

This explanation is that before the advent of the glaciers there were valleys, the tributaries entering the main valley with accordant grade (p. 177), as they should. Then both main and tributary valleys were occupied by glaciers which broadened and deepened them, but eroded the main valley the most. When the ice disappeared, the tributaries were discordant, and the depth of the main valley below the mouth of the tributary is the measure of the extent to which it was lowered by glacial erosion in excess of the lowering of the tributary. In some cases this discordance indicates glacial erosion of 1000 to 2000 feet, accompanying which was notable broadening.

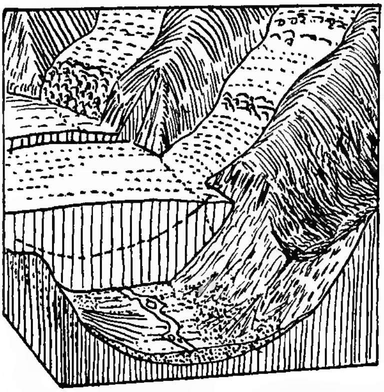


FIG. 150. — Relationships of tributary glaciers to hanging valleys. (After Davis.)

In the recent geological past valley glaciers have been far more extensive than now in many regions: in Alaska, Patagonia, New Zealand, the Alps, Norway, and many other places. During this period powerful glaciers, compared with which the largest glaciers of the Alps are mere pygmies, ploughed along through the mountain valleys for many thousands of years. It would seem strange if such glaciers failed to produce notable changes. It is, therefore, significant that the assemblage of forms here described are common to all such regions of former great glaciers, while they are not characteristic features of regions that were not glaciated. The great majority of students of glacial phenomena accept the evidence as conclusive that glaciers have been among the powerful agents of erosion. It is true that there are still some who are unwilling to accept the evidence; so at an earlier time there were some who long held out against the evidence that streams eroded their own valleys. In some cases, at least, the failure to accept the proofs of glacial erosion is due to the fact that the best-known glaciers are among the weakest. To use these glaciers of the Alps as a basis for interpretation of the power of great glaciers is quite like using a sluggish, modern brook as a basis for understanding the formation of the Colorado Canyon.

The full acceptance of the evidence of powerful glacial erosion carries with it the necessity of assigning to it a very profound influence in shaping the topography of many mountain regions of former great glaciers. Deep valleys have been eroded and the mountain topography sharpened. According to Penck and Brückner the present-day topography of the Alps is profoundly modified, and in places

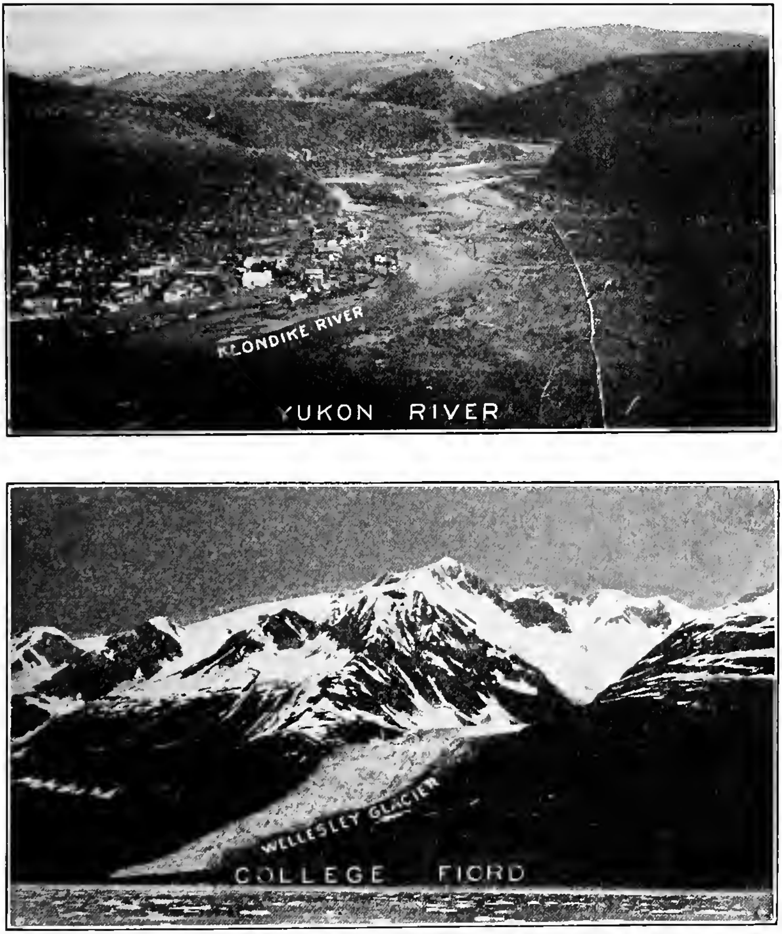


FIG. 151.—Accordant and hanging valleys. Upper view (Duclos) shows Klondike River joining the Yukon in the never-glaciated district near Dawson. Lower view shows a hanging valley in College Fiord, Alaska, made by glacial erosion.

determined, by glacial erosion. Many thousands of waterfalls occur where the streams from hanging tributaries descend the steepened slope of the main valleys, perhaps the most noted being the falls of the Yosemite (Pl. IX).

The Cirque or Kar. — Another noteworthy feature of glaciated mountain regions is the *cirque* or *kar*, an amphitheatre-like valley with steeply rising walls (Figs. 152, 153). Other names used for this form are *corrie* in Scotland, *botn* in Norway, *cwm* in Wales, *oule* in the Pyrenees, *caldare* and *zanoga* in the Carpathians. Cirques are apparently due to the erosive action of glaciers, eating backward at their heads. The exact nature of the process is not clearly understood, but it seems to be partly the erosive action of the downsliding snow against the cirque walls, and partly the scouring

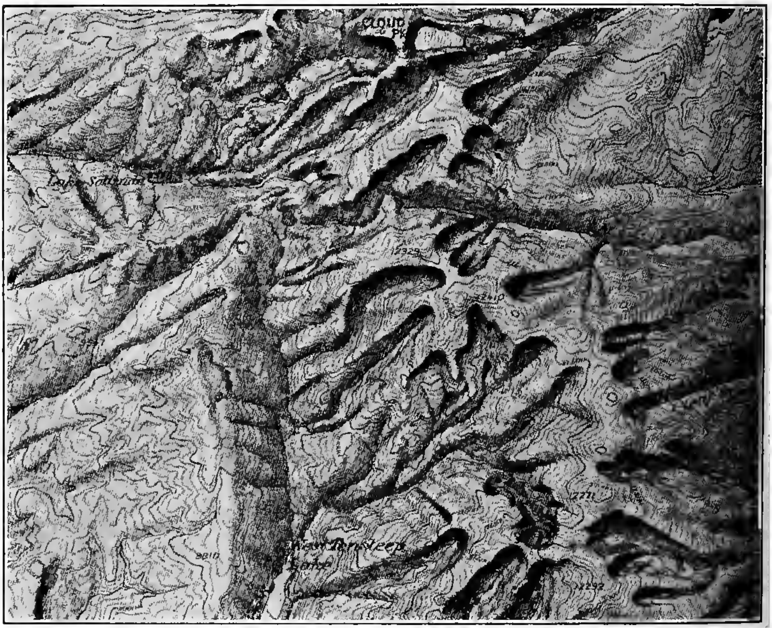


FIG. 152. — Cirques in the Rocky Mountains. (Darton.)

at the base of the slopes by outward motion of the ice that forms beneath the snow. At the base of the slopes the snow accumulates and here there is probably a downward, plunging motion, sharply eroding and deepening the valley bottom near the cliff base. This outward movement is indicated by the common presence of a great crack, called the *bergschrund*, extending deep in the névé near the cirque head. It has been suggested that alternate melting and freezing at the base of the bergschrund, introducing a sort of frost quarrying process, is the main factor in cirque formation; but it does not seem an adequate explanation, though it may be contributary.

FIG. 153.—Head of cirque in Canyon Creek, Glacier National Park. Cliff 3100 feet high.

Whatever the exact nature of the process, the result seems established. By it cirques are formed, enlarged, and caused to extend headward. By this cirque recession mountain ranges are sharpened, and divides are pushed backward. The cirques on one side of a mountain range often push their heads back into the area of others on the opposite side of the divide. There are all stages in the process, and it is apparently a potent factor in shaping the upper portions of mountains.

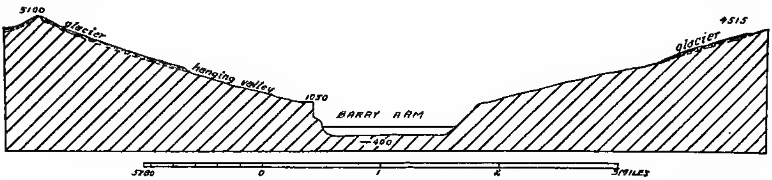


FIG. 154. — Cross-section of a fiord in Alaska. Vertical and horizontal scales the same.

Although the efficiency of ice as a powerful agent of erosion was proposed many years ago and has ever since been maintained by a body of workers, it is in only comparatively recent times that the full significance of hanging valleys and other features indicative of glacial erosion has been generally recognized. To those who recognize the significance of the evidence it seems so clear that the wonder is it was so long overlooked, and, when first proposed, was not accepted by some who now fully admit its convincing nature. While there are a few who still refuse to admit the force of the evidence, to the great majority of students of glacial phenomena it seems as obvious as that rivers have formed their valleys.

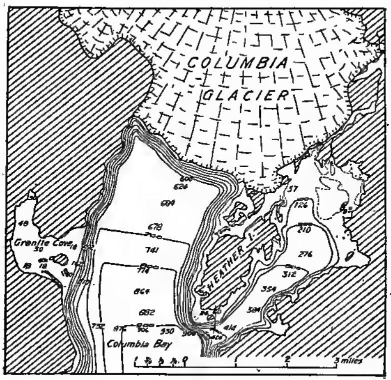


FIG. 155. — Two submerged hanging valleys in Alaska.

Glaciation in Fiords. — Where glacial erosion along a coastal region extended below sea level, or where the sea has been admitted by subsidence to the glacially eroded land, fiords are produced (Pl. V). To this origin is to be assigned a large part of the fiorded coast of Alaska, Patagonia, and Norway, and other coastal regions. The problem of fiord production without submergence has been studied by Muir, Gilbert, and others. One of the significant features is the *submerged hanging valley* (Fig. 155). In connection with deposition in Alaskan fiords during or after glaciation the glacio-fluviatile deposits have filled some deep fiords completely, and in others, terminal moraines in the sea, or *moraine bars* (Fig. 156), have been built by the receding tidal glaciers.

Distribution of Valley Glaciers. — The distribution of valley glaciers is practically the same as that of snow fields (p. 199), for in snow

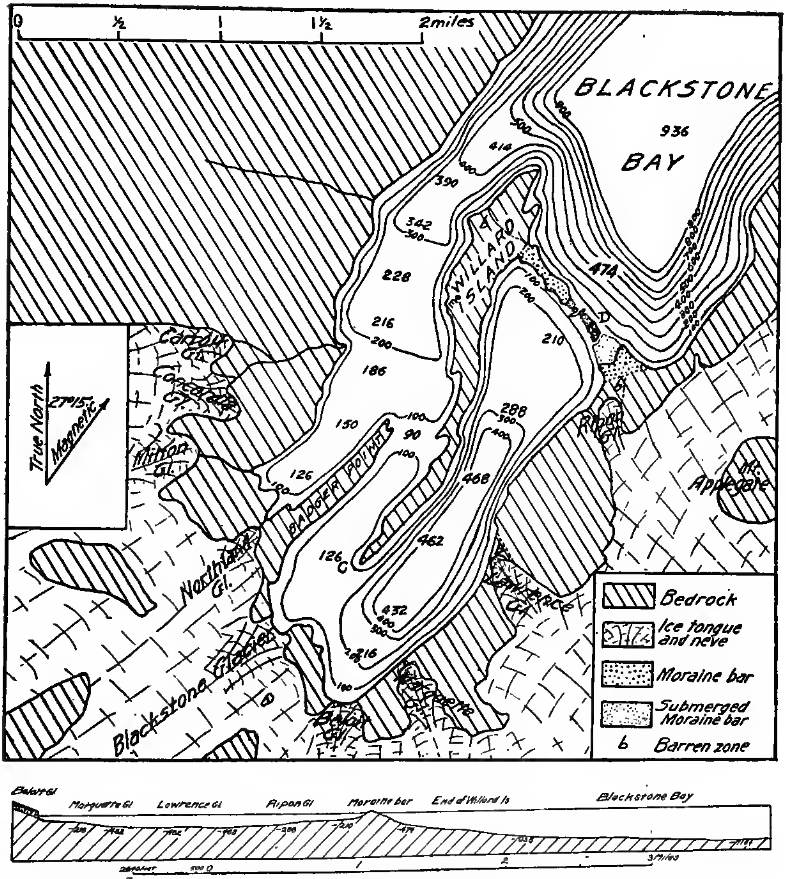


FIG. 156. — Map and profile of Alaskan fiord with moraine bar near Ripon Glacier.

fields glaciers are born. Even where snow fields give rise to ice sheets, valley glacier distributaries extend out from the ice sheet margins. Glaciers occur in all zones, but in the tropical zone are found only in the loftiest mountains, and even there are usually small. They increase in size and number toward the polar regions, and their termini descend.

In Europe valley glaciers exist in the Pyrenees, Alps, Carpathians, Caucasus, and Norway. No part of the British Isles rises high

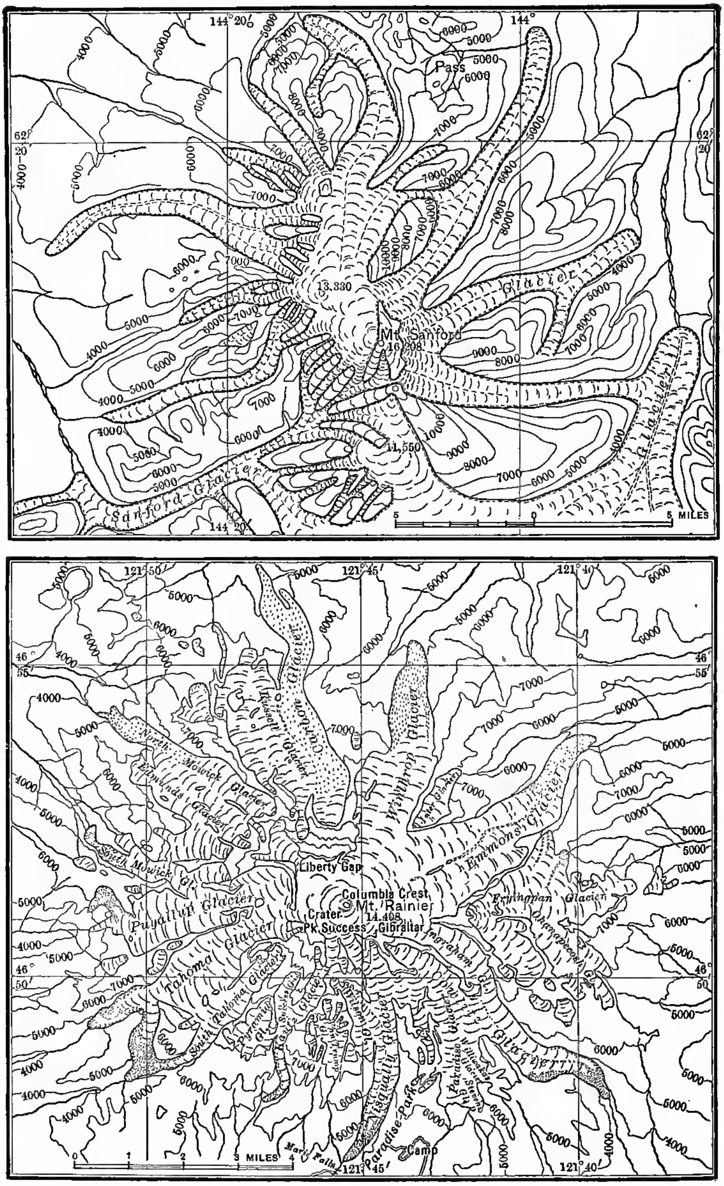


FIG. 157.—Radiating valley glaciers on Mt. Rainier in Washington and Mt. Sanford in Alaska. (U. S. Geol. Survey.)

enough for permanent snow fields. There are no glaciers in eastern North America, except possibly in the mountains of northern Labrador. In the Arctic islands to the north of Labrador there are many glaciers. There are a few small glaciers in Mexico, within the tropics, then none south of the San Bernardino, Sierra Nevada, and Cascades in California, Oregon, and Washington. There are many in northern United States, as on Mounts Rainier and Hood, and in the Glacier National Park and still more in British Columbia. North of this the number and size of the glaciers increase rapidly, culminating in Alaska (Figs. 157, 159).

No one can tell how many valley glaciers there are on the earth. There are certainly scores of thousands, for where the mountains are snow-capped, every valley extending from the snow fields has its glacier. There are about 2000 in the Alps, but in Alaska there are certainly tens of thousands. Only the very largest and most conspicuous are named, and even these are not yet thoroughly explored. Many glaciers larger than the Aletsch do not yet bear a name. Other regions of great and numerous glaciers are also almost unknown, as Patagonia, the Himalayas, and the islands of the Arctic.

Piedmont Glaciers

Malaspina Glacier, an Ice Plateau. — The Malaspina Glacier, at the base of Mt. St. Elias in Alaska, is the type of this class of glaciers.

Fig. 158. — Malaspina Glacier and Mt. St. Elias. (Russell.)

Several large valley glaciers and a number of small ones feed it, forming a low ice plateau fringing the seaward base of the mountains. This ice plateau is about 70 miles long in an east-west direction, and from 20 to 25 miles broad, and the total area is about 1500 square miles, making it larger than Rhode Island (Figs. 158, 159).

Relation to Valley Glaciers. — While forming a continuous plateau, each part, or lobe, of the glacier is supplied by one of the great valley glacier tributaries; that is, the glacier is composed of a series of coalesced piedmont bulbs. Accordingly, the different portions of the ice plateau are somewhat independent of the other portions, but are influenced by the particular valley glacier which supplies the ice.

Where the valley glaciers emerge from their mountain valleys, the ice is in vigorous movement and the surface is often broken by crevasses. Spreading beyond the mountain base, the ice flows less rapidly, but is still broken by many crevasses. With decreasing motion and increasing ablation, these crevasses gradually die out toward the margins. In general, the ice plateau has a fairly level

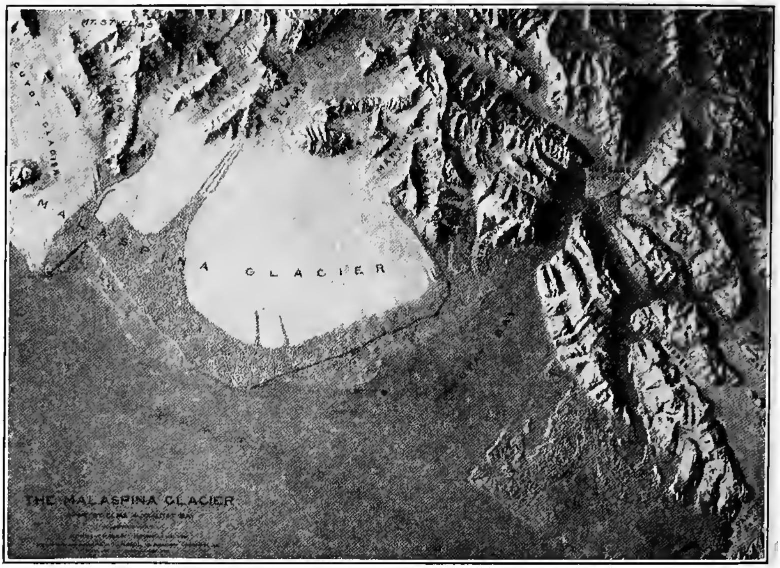


FIG. 159.— Malaspina Glacier and Yakutat Bay, Alaska. (Model by Lawrence Martin. Copyright, 1909, by the University of Wisconsin.)

surface, with undulations and minor irregularities. Its general elevation is from 1500 to 2000 feet, but it descends rapidly near the margin, where the base stands at about the sea level.

The Forest-covered Margin of Malaspina Glacier. — Most of the surface is of clear ice, though there are swirls of moraine upon it, and there are morainic bands between the lobes and around the margins. In the latter position the ice is completely covered with ablation moraine, which in places covers a width of five miles. In some portions of this moraine-covered area the ice has reached such a state of stagnation, and has become so deeply coated with moraine, that a forest grows upon it. There, spruce trees, cottonwood, and alders and other plants form a dense thicket, although a few feet beneath the surface in which they grow are hundreds of feet of glacial ice. It

FIG. 160. — The forest-covered border of Malaspina Glacier. Dead trees in foreground on outwash gravels. Living conifers in background on moraine-covered ice. (Russell.)

is estimated that there are from 20 to 25 square miles of forest on this piedmont glacier (Fig. 160).

Advance of One Lobe of the Malaspina. — In 1906 the eastern lobe of the Malaspina Glacier was subjected to a powerful thrust as a

FIG. 161. — The crevassed eastern border of Malaspina Glacier destroying trees. The broken blocks which appear like rock are glacial ice.

result of the abrupt advance of the Marvine Glacier. By this the ice was broken into a sea of crevasses, making this part of the glacier surface impassable. The advance and breaking of the glacier extended to the eastern margin, and overturned and destroyed most of the forest that had previously grown there (Fig. 161). The central and western portions of the glacier were undisturbed.

Outwash Gravels at Border of Malaspina. — The westernmost lobe of the Malaspina Glacier is rapidly retreating, but it still reaches the sea in Icy Bay, where icebergs are discharged from it. It also reaches the sea further east at Sitkagi Bluffs, though not there discharging icebergs. The remainder of the margin of the glacier rests on land,

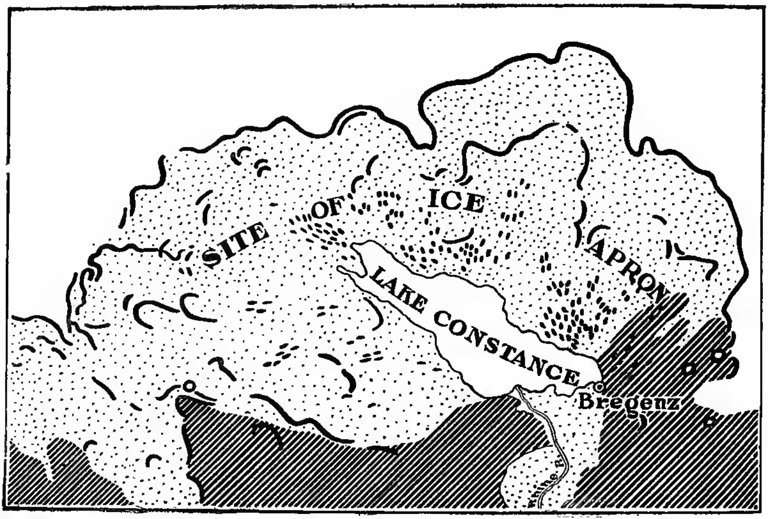
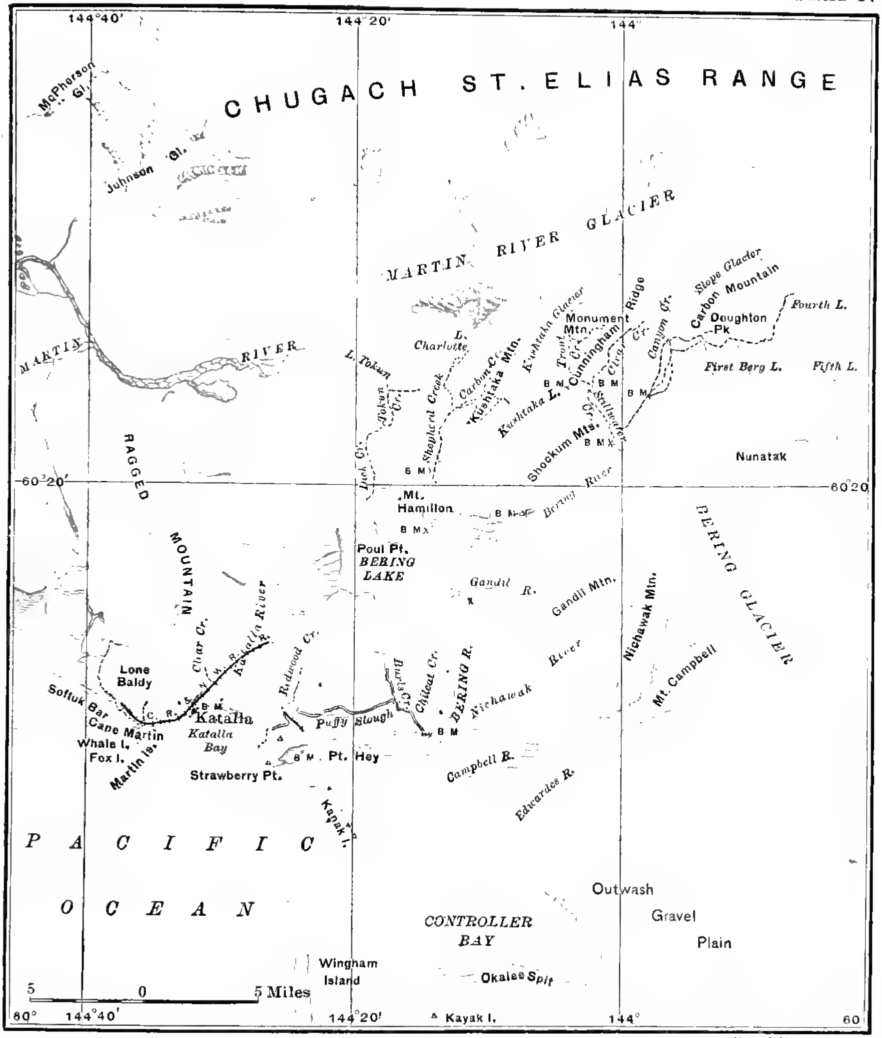


FIG. 162. — Site of a former piedmont glacier northwest of the Alps. (After Penck and Brückner.)

which, so far as can be seen, is chiefly made of outwash gravels deposited by the streams that issue from the ice. There are several large streams and innumerable small ones, issuing from ice tunnels along the margin. The larger streams are great torrents, heavily charged with débris, where they issue from the ice caves. They soon branch and subbranch into a multitude of distributaries, and quickly deposit the coarsest part of their load, thus building up a series of alluvial fans fringing the ice margin. The great amount of water is due to the fact that there is here an extensive surface of ice below snow line and close by the sea from which warm, damp winds prevail.

Other Piedmont Glaciers. — Near the Malaspina Glacier are other smaller piedmont glaciers and piedmont bulbs of individual glaciers which spread out at the mountain base without coalescing with others.



BERING GLACIER

Part of the Piedmont Bering Glacier, Alaska. The foothills south of Martin River Glacier contain valuable bituminous and anthracite coal deposits. The streams from the ice have isolated Bering Lake from Controller Bay. There are many more streams than are shown on the part of the outwash gravel plain east of Okalee Spit. Contour interval 200 feet. (From Chitina Quadrangle, United States Geological Survey.)

Farther west is another large piedmont glacier, the Bering (Pl. IV). Its area is not known, though apparently smaller than the Malaspina, which it otherwise resembles. Doubtless this type of glacier is also represented in other parts of the world, though we know of none that rival either the Malaspina or Bering.

Importance of Piedmont Glaciers. — During the Glacial Period, however, when valley glaciers were far more expanded than now in many mountains, the piedmont type of glacier was common. In the Alps, for example, ice bulbs expanded at the mountain base both on the north and south sides, and a piedmont glacier overspread a part of Switzerland (Fig. 162). They were likewise formed in the North American Cordillera. Therefore, although piedmont glaciers are not now very common or widespread, they are of importance as existing illustrations of a former condition whose effects are now plainly to be seen.

Continental Glaciers

Ice Caps and Ice Sheets. — As already stated, there are many ice caps on the islands of the Arctic, some of them of very small extent,

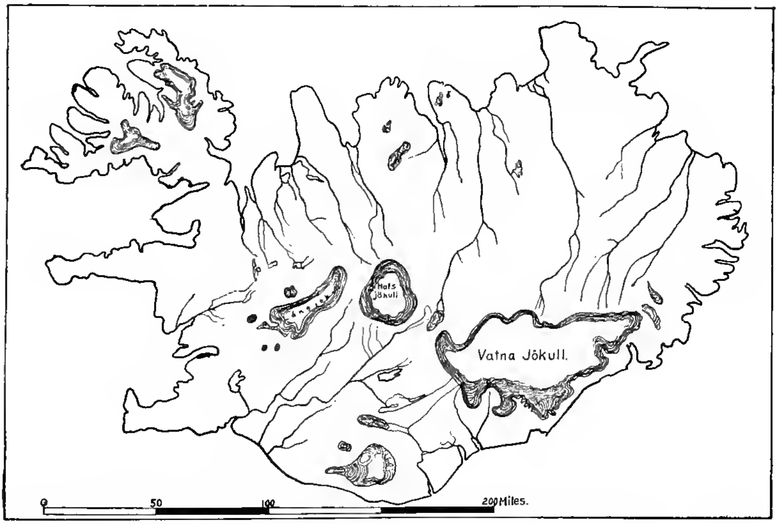


Fig. 163. — Vatna Jökull and other ice caps in Iceland.

while on the larger islands there are more extensive ice sheets. There are, however, only two ice sheets that are of sufficient proportions to warrant the name continental glacier, one covering much of Greenland, the other in the Antarctic. There are all gradations, from the ice sheet that covers all the land, as in Greenland, to vast snow fields sub-

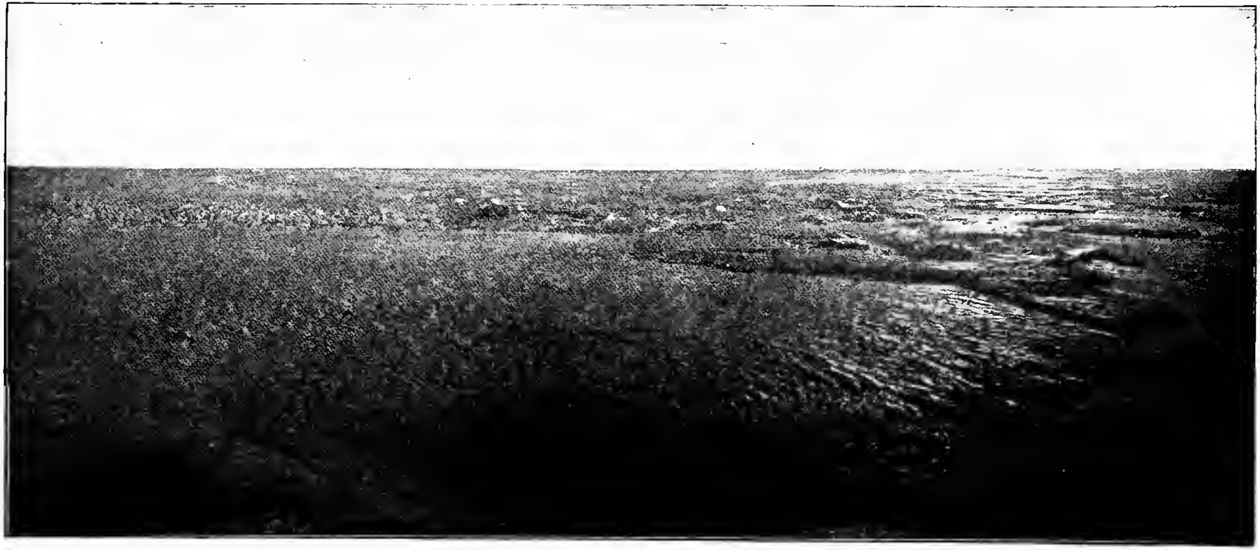


FIG. 164. — Photograph of the surface of the continental glacier in Antarctica. (von Drygalski.)

merging most of the land, as in Spitzbergen, and thence to snow fields feeding typical valley glaciers, or to small ice caps a few square miles in area (Fig. 163). The smaller ice caps resemble the large ice sheets in a small way; and the great snow fields and glaciers of the

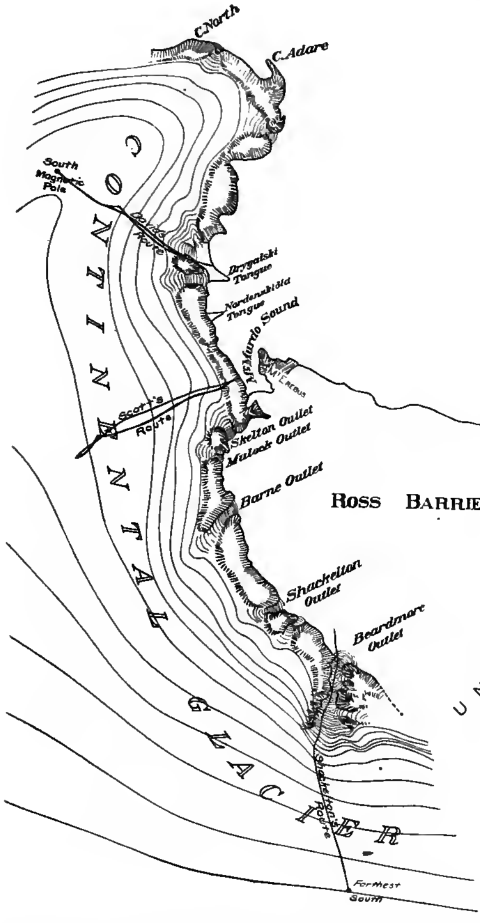


FIG. 165.—Beardmore Glacier and other distributaries which connect the continental glacier of the interior of Antarctica with the piedmont glacier called Ross Barrier. (Hobbs, after Scott and Shackleton.)

Spitzbergen type are intermediate in character between ice sheets and valley glaciers. These glaciers may, therefore, be omitted from further description, and attention be paid primarily to the two great areas of existing continental glaciers.

The Antarctic Ice Sheet. — Within a few years much has been learned about the conditions in the Antarctic, though this vast region is still in large measure unexplored and unknown. It is an ice-bound region, the land covered with snow and ice, and the sea covered with floating ice. The snow line extends to sea level, and snow banks and glaciers project from the land around the entire coast line. Whether the land is one great continent, mostly buried beneath snow and ice, or whether it is a series of ice-submerged islands is not yet known. It is, however, certain that the South Pole, which lies in the midst of this region, is located on a continental glacier, — the largest at present existing on the earth. What the size of the continental glacier is, cannot be stated, but it cannot be less than 5 million square miles in area (Fig. 164).

The Continental Glacier of Antarctica. — Around the coast line is mountainous land with snow and glaciers upon it. But back from the coast the snow has accumulated as an ice cap, which Shackleton found to be a vast, snow-covered ice plateau, rising to about 10,000 feet 110 miles from the South Pole, where he turned back. Amundsen and Scott subsequently found that it extended to the pole itself.

Beardmore Glacier and Other Distributaries. — From the ice plateau of the Antarctic continental glacier there are outlets along valleys in the mountains, down which valley glacier tongues extend. These vary in size, but one, the Beardmore Glacier (Fig. 165), is over 125 miles long, and from 10 to 20 miles wide, with a total area of over 5000 square miles; yet it is merely one of many distributaries of the vast continental glacier. The depth of the inland ice is unknown, but it may well be several thousand feet. It is able to accumulate until its depth necessitates outward flowage, for there is no other source of loss than evaporation, and the drifting of the loose snow by the wind. There is no melting, and probably no other form of precipitation than that of snow.

The Great Ice Barrier. — The shores of Ross Sea, near Victoria Land, are bordered by an ice cliff 500 miles long, called the Great Ice Barrier. This cliff (Fig. 166), which rises from 50 to 280 feet above the water, is the edge of a vast plain of ice — a sort of piedmont glacier — which stretches for a distance of over 300 miles southward and is evidently afloat. Into it pour numerous great glaciers, and it is moving seaward at the rate of about 1600 feet a year. Although supplied with ice from the glaciers that enter it, and given its motion by them, it is said to be composed of compacted snow ice, not of glacier ice. The explanation is that the annual snowfall adds layer upon layer on the ice barrier while the sea water melts the glacier ice at the bottom. It is a peculiar form of glacier.

Antarctic Icebergs. — From the Great Ice Barrier, and from other parts of the coast of Antarctica, icebergs are discharged into the sea. Those from the ice barrier are especially noteworthy for their great size and tabular form. Sometimes huge sections of the ice cliff break off and float away, looking like great islands of ice. Scott reports a tabular iceberg 5 or 6 miles long and about as wide, though few exceed a square mile in area. Usually they rise no more than 150 feet above the water, though one measured 240 feet.

The Greenland Ice Sheet. — Though smaller, more is known about the continental glacier of Greenland than about that of Antarctica. Greenland has an area of about 827,275 square miles, and all but a fringe of coast line is covered with an ice sheet whose total area is

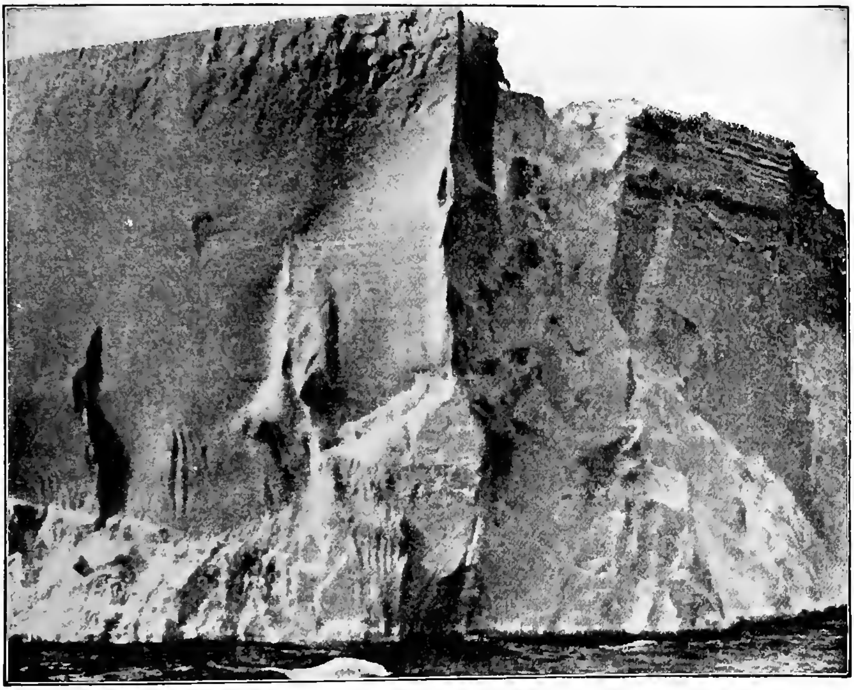


Fig. 166. — The Great Ice Barrier of Antarctica. (Scott.)

estimated to be about 715,400 square miles, or over eight times the area of Great Britain. This ice rests upon a low mountainous land, judging from the topography along the coast, where the mountains commonly rise 2000 to 3000 feet or more above sea level (Fig. 167).

The Interior of Greenland a Snowy Desert. — Greenland has been crossed in the south by Nansen, De Quervain, and Koch, and in the north by Peary and Rasmussen, but the greater part is an unknown desert waste of snow. The surface rises toward the interior, which is a great, snow-covered ice dome, attaining an elevation of at least 8000 to 10,000 feet, and with the ice several thousand feet in depth.

So far as known, no land rises above this interior, which, next to that of Antarctica, is the most absolute desert in the world. There is no sign of life upon it; the temperature never rises to the melting point; but, through all seasons of the year, there is snow and bitter cold. The snowfall that descends upon the interior finds its way outward

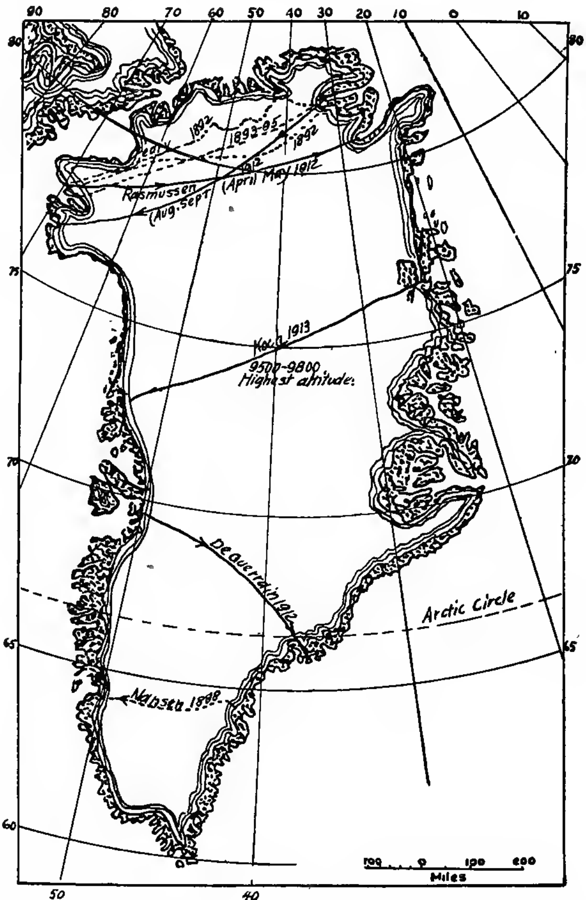


FIG. 167.—The continental glacier in Greenland. Coastal fringe of land stippled.

in two ways: (1) by the winds, which prevailing blow down the surface of the ice sheet; (2) by the slow outward flow of the ice, which spreads seaward under the load of the accumulating snow. We have no knowledge as to the rate of flow of the ice sheet, but the fact that there is little or no crevassing indicates that it is a very slow movement.

Smooth Ice of Border Region. — Spreading northward, southward, eastward, and westward from the central area of accumulation the ice reaches lower altitudes, and, in the south, lower latitudes. It therefore reaches into the zone of ablation. There is, therefore, a fringe, broadening southward, where the surface is exposed to summer melting; and there the snow is removed and the glacier ice revealed.

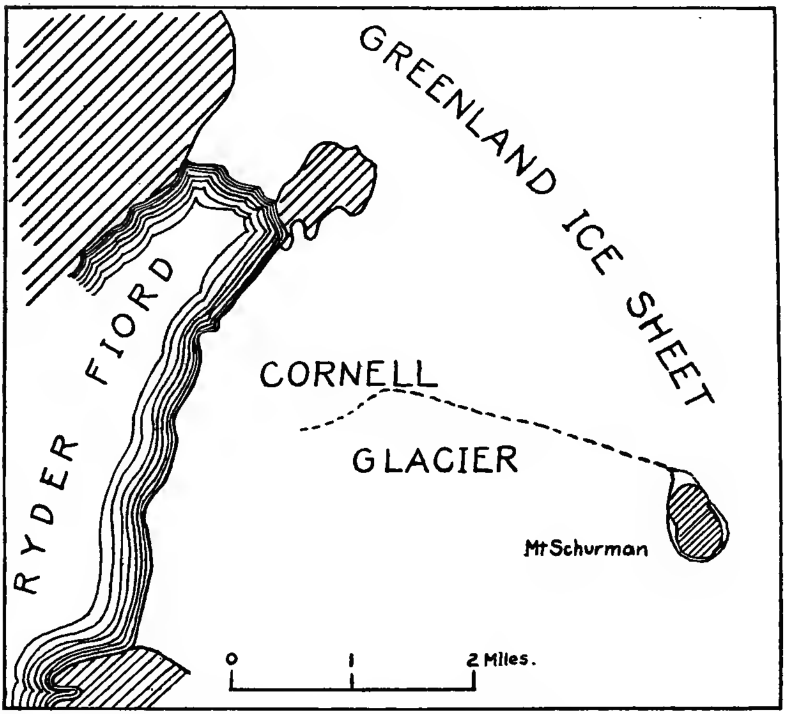


FIG. 168. — The Cornell Glacier, a distributary of the Greenland ice sheet. Mt. Schurman, a nunatak. (Tarr and Bonsteel.)

In its general characteristics this ice is like that of valley glaciers. The movement is still slow, and there is little crevassing, though some domes of crevassed ice appear, where the glacier is evidently passing over the crests of buried hills. There is no moraine at the surface, though dust, blown from the land, is present in the bottom of minute wells which they have melted in the ice. Everywhere is a vast expanse of clear ice, little broken, but with undulating surface, rising toward the snow-covered interior (Fig. 169).

Nunataks. — In the intermediate coastal fringe the conditions are entirely changed. Here peaks, called *nunataks*, project above the ice, forming rock islands in a sea of ice, and from them bands of moraine extend seaward.

Glacier Distributaries. — The outward-flowing ice moves more freely down the valleys between the peaks, giving rise to valley tongues, or distributaries. The largest of these reach the sea in the fiords, which are the continuation of the valleys through which the ice is flowing (Fig. 168). These rapidly moving valley tongues are crevassed, and some are a sea of crevasses. Like valley glaciers, they may bear lateral moraines in their lower portions, derived from the bordering cliff which here rises above the ice surface. Between the valley tongues the margin of the ice sheet rests against the land. Thus the border of the Greenland ice sheet is very irregular, with a land margin for a large part of the distance, but with tongues projecting beyond this into the sea. While there is loss of ice by ablation, a large part of the Greenland Glacier discharges into the sea through the rapidly moving distributaries. Between the tidal glacier tongues the hilly land rises, so that a large part of the Greenland coast is a land fringe, with the ice sheet extending up to it, and discharging down its valleys. This fringe of land broadens toward the south. Where it is high enough, it has its own individual valley glaciers, and, where a broad enough area is present, as on Disco Island, its own ice cap.

Some of these ice distributaries are very large. The largest, so far as is known, is the Humboldt Glacier, which is 60 miles wide where it enters the sea. There are many that are 5 miles in width, and their ice cliffs rise 200 to 300 feet above the water. They advance at a rate that, for glaciers, is very rapid. Thus, one which is five miles wide moved during the period of observation at the rate of 5 feet a day; another, larger glacier, at a rate of 48 to 65 feet a day; and one, the Upernavik Glacier, has a reported movement of 75 feet a day.

Greenland Icebergs. — With such rapid motion, there is, naturally, abundant discharge of icebergs, otherwise the glacier fronts would be pushed far out to sea. Almost constantly pieces are crashing from the ice front, and as they fall into the water, or rock back and forth in it, they generate ring waves, which sweep far out in the fiord and cause breakers on the coast. Some of the ice fragments fall from the cliff, a few hundred pounds or a few tons at a time, or, now and then, great masses hundreds of tons in weight. In other cases it appears probable that large blocks are broken off by the buoyancy of the water into which the glacier advances till its end is afloat.

The fiord is dotted with ice, and in places quite filled with it; but it does not remain there, for the winds that blow off the glacier, and the fresh water that flows from the glacier, cause an outward current, and the bergs travel out to the open sea. There they drift about, and many of them travel southwards past Newfoundland before they finally melt. It was an iceberg from Greenland which caused the wreck of the steamer *Titanic* in 1912.

While not comparable in size with the huge tabular icebergs of the Antarctic, many of the Greenland icebergs are nevertheless of great size, the largest being a mile across. They rise 100 to 200 feet out of the water and sink 6 or 7 times as far below the surface, so that an iceberg may be 1000 or 1500 feet high, and much larger in other directions. As it floats slowly in the current its irresistible force is sometimes shown when it runs into a shoal and begins to break to pieces, though no reason for the breaking can be seen. They also change in shape through melting and turning over. By this wide dispersal of the ice, the snow that falls upon the interior of Greenland is finally returned to the sea, and, as it melts, rock fragments that the glacier bore along are dropped over the sea floor.

Marginal Phenomena. — Where the Greenland ice sheet rests on the land, it usually has a slope of greater or less steepness, due to

FIG. 169. — The Greenland ice sheet with a nunatak and the Cornell Glacier distributary, terminating in Ryder Fiord, which was excavated by glacial erosion.

melting in the neighbourhood of the warmed land, and, as in valley glaciers, there is often a depression between the ice and the land, in which a muddy stream flows. Here and there, also, there are marginal lakes, in which the glacial streams are building deltas and other deposits. There is, however, no such volume of water in this climate as there is in the warmer climate in which the Alaskan and other valley glaciers of the temperate latitudes terminate.

The lower layers of the ice sheet are charged with rock fragments, which have been removed from the surface over which the ice has moved. These are revealed at the base of the ice along the land margin, but a short distance above the base the ice is clear and free from morainic materials. These rock fragments show signs of the powerful grinding to which they have been subjected, and the stones are often well striated, while the rocks on which the glacier rests are also striated, polished, and worn into the roches moutonnées form. At the base of the ice cliff a terminal moraine is forming by the accumulation of the rock fragments brought forward to the edge of the ice. It fringes the ice margin closely and, therefore, leaves a definite record of the stand of the ice whenever it remains long enough at a given position.

Glacial Erosion in Greenland. — The Greenland ice sheet has formerly been more extensive than now, and has left records of its presence, similar to those left by valley glaciers. There are roches moutonneés forms; striated pebbles and boulders, often of a different kind from rocks on which they rest; grooved and polished rock surfaces; and in favourable situations, thin deposits of till. But the Greenland Glacier does not carry a great enough load of morainic material to form extensive deposits when the ice melts away. The fiords through which the ice formerly extended are smoothed and straightened by glacial erosion, and that they are also deepened is proved by the presence of many hanging valleys. That the movement of a glacier 2000 feet deep, or more, should wear away the bed upon which it presses with a weight of 800 pounds per square inch, dragging its rock-shod mass heavily over the valley bottom at the rate of from 25 to 50 feet a day, is not difficult to believe. That it should wear the valley bottom deeply requires only belief in the continuation of the process for a long period of time. Here again, where we know glaciers formerly to have been, we find the evidence that they have eroded profoundly. A very considerable part of the irregularity of the coast line of Greenland is the work of glacial erosion, dissecting a previously less rugged land (Fig. 169).

References to Literature

Louis Agassiz. Études sur les Glaciers, Neuchâtel, 1840, 347 pp.; Nouvelles Études et Experiences sur les Glaciers Actuels, Paris, 1847, 598 pp.

E. C. Andrews. The Ice Flood Hypothesis of the New Zealand Sound Basins, Journ. Geol., Vol. 14, 1906, pp. 22–54.

W. W. Atwood. Glaciation of the Uinta and Wasatch Mountains, Prof. Paper 61, U. S. Geol. Survey, 1909, 96 pp.

W. J. Bently. Studies of Frost and Ice Crystals, Monthly Weather Review, 1907.

T. G. Bonney. Ice Work, Past and Present, New York, 1896, 284 pp.

E. Brückner. Klimaschwankungen und Völkerwanderungen im XIX Jahrhundert, I tern. Wochensch. f. Wissenschaft, Kunst und Technik, March, 1910.

J. V. Buchanan. On Ice and its Natural History, Nature, Vol. 78, 1908, pp. 379–382.

E. C. Case. Experiments in Ice Motion, Journ. Geol., Vol. 3, 1895, pp. 918–934.

T. C. Chamberlin. Glacial Studies in Greenland, Journ. Geol., Vol. 2, 1894, pp. 649–666, 768–788; Vol. 3, 1895, pp. 61–69, 198–216, 469–480, 565–582, 669–681, 833–843; Vol. 4, 1896, pp. 582–592; Vol. 5, 1897, pp. 229–240; Bull. Geol. Soc. Amer., Vol. 6, 1895, pp. 199–220.

T. C. Chamberlin and R. D. Salisbury. Geologic Processes, New York, 1905, pp. 244–323.
W. O. Crosby. The Hanging Valleys of Georgetown, Colorado, Amer. Geol., Vol. 32, 1903, pp. 42–48.
W. M. Davis. Glacial Erosion in France, Switzerland, and Norway, Geographical Essays, Boston, 1909, pp. 635–689; The Sculpture of Mountains by Glaciers, *ibid.*, pp. 617–634; Der Glaziale Zyklus, Erklärende Beschreibung der Landformen, Leipzig, 1912, pp. 401–462; Glacial Erosion in North Wales, Quart. Journ. Geol. Soc., London, Vol. 65, 1909, pp. 281–350.
E. von Drygalski. Zum Continent des Eisigen Südens, Berlin, 1904, 668 pp.; Die Grönlande Expedition der Gesell. für Erdkunde, Berlin, 1897, 2 vols.; see also references to literature on Antarctic glaciers in Hobbs's Characteristics of Existing Glaciers.
S. Finsterwalder. Der Vernagtferner, Wissenschaftliche Ergänz. zur Zeitschrift des D. u. Ö. Alpenvereins, 1 Band, 1 Heft, 1897, 112 pp.
A. Forel and M. Lugeon. Les Variations Periodiques des Glaciers des Alps, Jahrbuch des Sch. Alp. Verein, annual reports beginning in 1880.
H. Gannett. Lake Chelan, Nat. Geog. Mag., Vol. 9, 1898, pp. 417–428.
E. J. Garwood. On the Origin of Some Hanging Valleys in the Alps and Himalayas, Quart. Journ. Geol. Soc., Vol. 58, 1902, pp. 703–717; Features of Alpine Scenery Due to Glacial Protection, Geog. Journ., Vol. 36, 1910, pp. 310–339.
G. de Geer. Guide de l'Excursion au Spitzbergen, 11th International Geological Congress, Stockholm, 1910.
G. K. Gilbert. Glaciers, Harriman Alaska Expedition, Vol. 3, 1904, 231 pp.; Systematic Asymmetry of Crest Lines in the High Sierra of California, Journ. Geol., Vol. 12, 1904, pp. 579–588; Moulin Work under Glaciers, Bull. Geol. Soc. Amer., Vol. 17, 1906, pp. 317–320.
A. Heim. Handbuch der Gletscherkunde, Stuttgart, 1885, 560 pp.
J. Henderson. Extinct and Existing Glaciers of Colorado, University of Colorado Studies, Vol. 8, 1910, pp. 33–76.
H. Hess. Die Gletscher, Brunswick, 1904, 426 pp.; Alte Talböden im Rhonegebiet, Zeitschrift für Gletscherkunde, Vol. 2, 1908, pp. 321–361.
W. H. Hobbs. Characteristics of Existing Glaciers, New York, 1911, 289 pp.
D. W. Johnson. Hanging Valleys of the Yosemite, Bull. Amer. Geog. Soc., Vol. 43, 1911, pp. 826–837, 890–903.
W. D. Johnson. The Profile of Maturity in Alpine Glacial Erosion, Journ. Geol., Vol. 12, 1904, pp. 569–578.
A. C. Lawson. The Geomorphogeny of the Upper Kern Basin, Bull. 3, Dept. Geol. Univ., California, 1904, pp. 291–376.
D. F. Lincoln. Glaciation in the Finger-Lake Region of New York, Amer. Journ. Sci., Vol. 144, 1892, pp. 290–301; Vol. 147, 1894, pp. 105–113.
W J McGee. Glacial Canyons, Journ. Geol., Vol. 2, 1894, pp. 350–364.
Lawrence Martin. The Glaciers of Alaska, pp. 1–22, the Glaciers and Glaciation of Prince William Sound and the Lower Copper River, pp. 232–485, — in Tarr and Martin's Alaskan Glacier Studies, Washington, 1914; Geology and Physiography of Glacier Bay and Yakutat Bay, Yukon-Malaspina Excursion, 12th International Geological Congress, Guidebook No. 10, Excursion C 8, Ottawa, 1913, pp. 121–162; Glaciers and International Boundaries, Scientific American Supplement, Vol. 76, 1913, pp. 129, 136–138; Alaskan Glaciers in Relation to Life, Bull. Amer. Geog. Soc., Vol. 45, 1913, pp. 801–818.
E. de Martonne. Sur la Formation des Cirques, Annales de Géographie, Vol. 10, 1901, pp. 10–16.
F. E. Matthes. Glacial Sculpture of the Bighorn Mountains, 21st Ann. Rept., U. S. Geol. Survey, Part 2, 1900, pp. 167–190.
M. Mougin, C. J. M. Bernard, M. G. Flusin, and Others. Études Glaciologiques, Tirol Autrichien, Savoie et Pyrénées, Ministère de l'Agriculture, Paris, Tome I, 1909, 112 pp.; Tome II, 1910, 140 pp.; Tome III, 1912, 166 pp.

F. Nansen. First Crossing of Greenland, New York, 1892; Farthest North, 2 vols., New York, 1897.

O. Nordenskjöld. Die Polarwelt und ihre Nachbarländer, Leipzig, 1909, 220 pp.; Einige Beobachtungen über Eisformen und Vergletscherung der Antarktischen Gebiete, Zeitschrift für Gletscherkunde, Vol. 3, 1909, pp. 321–334.

V. Paschinger. Die Schneegrenze in Verschiedenen Klimaten, Petermanns Mitteilungen, Ergänzungshaft No. 173, 1912, 93 pp.

R. E. Peary. Northward over the Great Ice, New York, 1897; The Inland Ice of Greenland, Goldthwaite's Geog. Mag., Vol. 1, 1891, pp. 83–90.

A. Penck. Glacial Features in the Surface of the Alps, Journ. Geol., Vol. 13, 1905, pp. 1–19.

A. Penck and E. Brückner. Die Alpen in Eiszeitalter, 3 vols., Leipzig, 1909.

A. Penck, E. Brückner, and L. du Pasquier. Le Système Glaciaire des Alps, Bull. Soc. Sc. Nat. de Neuchâtel, Vol. 22, 1894, 86 pp.

H. Philipp. Ergebnisse der Filchner Vorexpedition nach Spitzbergen 1910, Petermanns Mitteilungen, Ergänzungsheft 179, Gotha, 1914, 79 pp.

G. Quincke. The Formation of Ice and the Grained Structure of Glaciers, Nature, Vol. 72, 1905, pp. 543–545.

C. Rabot. Revue de Glaciologie, Ann. du Club Alpin Français, Vol. 28, Paris, 1902; *ibid.*, No. 2, Vol. 29, Paris, 1903; *ibid.* No. 3, Mémoires de la Société Fribourgoise des Sciences Naturelles, Vol. 5, 1909; Glacial Reservoirs and their Outbursts, Geog. Journ., Vol. 25, 1905, pp. 534–548.

H. Reck. Glazialgeologische Studien über die Rezenten und Diluvialen Gletschergebiete Islands, Zeitschrift für Gletscherkunde, Vol. 5, 1911, pp. 241–297.

H. F. Reid. The Mechanics of Glaciers, Journ. Geol., Vol. 4, 1896, pp. 912–928; Glacier Bay and Its Glaciers, 16th Ann. Rept., U. S. Geol. Survey, Part 1, 1896, pp. 421–459; Glaciers of Mt. Hood and Mt. Adams, Zeitschrift für Gletscherkunde, Vol. 1, 1907, pp. 112–132; Variations of Glaciers, reports of the International Committee on Glaciers, Journ. Geol., Vol. 3, 1895, pp. 278–288; and annually in the same journal; see also Archives des Sciences Physiques et Naturelles, Vol. 2, Geneva, 1896, pp. 129–147, and annually up to 1905; and Zeitschrift für Gletscherkunde, Vol. 1, 1907, pp. 161–181, and annually in the same journal.

I. C. Russell. Glaciers of North America, Boston, 1897, 210 pp.; Existing Glaciers of United States, 5th Ann. Rept., U. S. Geol. Survey, 1885, pp. 303–355; Glaciers of Mt. Rainier, 18th Ann. Rept., U. S. Geol. Survey, Part 2, 1897, pp. 349–415; Second Expedition to Mt. St. Elias, 13th Ann. Rept., U. S. Geol. Survey, Part 2, 1892, pp. 7–91; The Quaternary History of Mono Valley, California, 8th Ann. Rept., U. S. Geol. Survey, Part 1, 1889, pp. 261–394; A Note on the Plasticity of Glacial Ice, Amer. Journ. Sci., Vol. 153, 1897, pp. 344–346; The Influence of Débris on the Flow of Glaciers, Journ. Geol., Vol. 3, 1895, pp. 823–832.

R. D. Salisbury. The Greenland Expedition of 1905, Journ. Geol., Vol. 3, 1895, pp. 875–902; *ibid.*, Vol. 4, 1896, pp. 796–810.

R. F. Scott. Results of the National Antarctic Expedition, Geog. Journ., Vol. 25, 1905, pp. 353–373; **H. T. Ferrar**, *ibid.*, pp. 373–386.

N. S. Shaler and W. M. Davis. Illustrations of the Earth's Surface, Glaciers, Boston, 1881.

W. H. Sherzer. Glaciers of the Canadian Rockies and Selkirks, Smithsonian Contributions to Knowledge, Vol. 34, 1907, 135 pp.

R. S. Tarr. The Margin of the Cornell Glacier, Amer. Geol., Vol. 20, 1897, pp. 139–156; Former Extension of Cornell Glacier near the Southern End of Melville Bay, Bull. Geol. Soc. Amer., Vol. 8, 1897, pp. 215–268; Valley Glaciers of the Upper Nugsuak Peninsula, Amer. Geol., Vol. 19, 1897, pp. 262–267; Lake Cayuga a Rock Basin, Bull. Geol. Soc. Amer., Vol. 5, 1894, pp. 339–356; Some Instances of Moderate Glacial Erosion, Journ. Geol., Vol. 13, 1905, pp. 160–173; The Properties of Ice (with J. L. Rich), Zeitschrift für Gletscherkunde, Vol. 6, 1912, pp. 225–249; Physiography and Glacial Geology of the Yakutat Bay Region, Alaska, Prof. Paper 64, U. S. Geol. Survey, 1909, pp. 11–144; Glacial Erosion in Alaska, Pop. Sci. Monthly, Vol. 71, 1907, pp. 99–119; Some Phenomena of the Glacier Margins in the Yakutat Bay Region, Alaska, Zeitschrift für Gletscherkunde, Vol. 3, 1909, pp. 81–110; The Theory of Advance of Glaciers in Response to Earthquake Shaking, *ibid.*, Vol. 5, 1910, pp. 1–35; The Glaciers and Glaciation of Alaska, Science, N. S., Vol. 35, 1912, pp. 241–258.

R. S. Tarr and Lawrence Martin. The Glaciers and Glaciation of Yakutat Bay, Alaskan Glacier Studies, Washington, 1914, pp. 23–231; An Experiment in Controlling a Glacial Stream, Annals Assoc. Amer. Geographers, Vol. 2, 1912, pp. 29–40.

T. Thoroddsen. Die Gletscher Islands, Petermanns Mitteilungen, Vol. 32, 1906, pp. 163–208.

J. Tyndall. The Glaciers of the Alps, New York, 1896; Forms of Water, New York, 1872.

W. Upham. Physical Conditions of the Flow of Glaciers, Amer. Geol., Vol. 17, 1896, pp. 16–29.

G. F. Wright. Ice Age in North America, New York, 1889, 1911, 741 pp.

Zeitschrift für Gletscherkunde. Für Eiszeitforschung und Geschichte des Klimas. Edited by Eduard Brückner, Vienna, Austria. Annual volumes beginning in 1907.

TOPOGRAPHIC MAPS

Glaciers

Controller Bay, Alaska, 601 A.
Coast Survey Chart of Glacier Bay, No. 8306.
Chitina, Alaska, 601.
Valdez Bay and Vicinity, Alaska, 602 B.
Nizina District, Alaska, 601 B.
Mt. Hood, Oreg.
Mt. Adams, Wash.
Glacier Peak, Wash.
Shasta Special, Cal.
Fremont Peak, Wyo.

Cirques or Kare, and Glaciated Mountains

Chief Mt., Mont.
Copper Mt., Alaska
Grand Teton, Wyo.
Lake Placid, N.Y.
Cloud Peak, Wyo.
Yosemite Valley, Cal.
Gilbert Peak, Utah
Kintla Lakes, Mont.
Mt. Lyell, Cal.
Juneau Special, Alaska
Silverton, Colo.
Georgetown, Colo.

For tidal glaciers, bulb glaciers, glaciated troughs, hanging valleys, valley trains, glaciated mountains, and fiords see the eight coloured contour maps in pocket of Tarr and Martin's *Alaskan Glacier Studies;* recent Professional Papers and Bulletins of the Alaskan Division of the U. S. Geol. Survey; and Coast Survey Charts, Nos. 8002 and 8550.

CHAPTER IX

THE GLACIAL PERIOD

Importance of Glacier Study to Man

While glaciers are among the noteworthy phenomena of physical geography, and possess features of general interest, there is an added reason for studying them in the fact that one of the most recent episodes in geological history was the great extension of glaciers in mountain regions where they still exist, as already stated, and also their development in regions where glaciers are no longer present. Among these places are northeastern North America and northwestern Europe — regions now densely settled. The effects of this former glaciation are plainly stamped upon the surface of the country. They have exerted a profound influence on the development of the regions from which the ice has disappeared, particularly in the United States and Europe.

Evidence of Former Glaciation

The former presence of ice sheets in Europe and North America where no glaciers now exist is plainly indicated by a number of phenomena: (1) over wide areas there are both stratified and unstratified deposits like those now being made in association with glaciers. There are pitted plains, there are moraines, there is till, and all the kinds of deposits to be expected where glaciers have been, and many of them of a kind that no other agency than ice is now known to make. (2) Scattered through and over these deposits are rock fragments, large and small, of a totally different kind from those of the region, but known to exist in other sections, which other evidence indicates to have been the region from which the ice sheets moved. Some of these fragments are boulders of huge size, often hundreds, and even thousands, of tons in weight. No other agency than ice is competent to transport such huge masses so far from their source, which is often scores and even hundreds of miles distant. (3) The boulders and pebbles are striated, as are those carried by living glaciers; and ice is the only agency known to be capable of this result. (4) The bed rock is also grooved, striated, polished, and rounded into the roches moutonnées, just as is the case at the front of the Greenland ice sheet and the valley glaciers of the Alps, Alaska, and other mountain regions. These grooves point toward the region from which the rock fragments have been moved; and they extend with a regularity and definiteness that no other agent of erosion than glacial flow could give. (5) The roches moutonnées forms also point toward the source from which the ice came, for one side is worn more than the other. The side from which the ice came, called the *stoss* side, is smoother and worn more than the opposite or *lee* side; and from the roches moutonnées as well as from the striæ one can tell the direction of the ice motion. Thus three evidences clearly point the same way: (*a*) the rock fragments, (*b*) the striæ, (*c*) the roches moutonnées. (6) There are hanging valleys, U-shaped valleys, truncated spurs, and other evidences of powerful glacial erosion in places where the ice moved freely along valleys. (7) Associated with all these phenomena there has been a rejuvenation of streams, as a result of partial or complete filling of valleys that existed prior to the Glacial Period. By this rejuvenation lakes have been formed in great abundance, rivers have been forced to cut gorges, and waterfalls have been developed in great numbers. (8) Along a sinuous belt, extending from sea level and passing across plains and over hills and even low mountains, such as the Appalachians, there is an accumulation resembling the terminal moraines of valley glaciers, and on the outer side of this, there are deposits of outwash gravels. (9) That this terminal moraine belt traces the former front of the glacier is clearly indicated by the fact that on one side of it all the phenomena mentioned above are well developed, while on the other side the phenomena are more or less completely absent. The fact that there were earlier advances, in which ice sheets reached farther than the terminal moraine of the last advance, has made this moraine a less definite line of demarcation than it would otherwise be.

Early Explanations of Phenomena

The Problem of the Erratics. — Some of the phenomena mentioned above were recognized very early. Thus the recognition of foreign rocks gave rise to the appellation *erratics*, still used for glacial boulders. The erratics are often large and unnatural, they are often grouped, and they are sometimes strangely perched, even so that they may be rocked by the hand. Among primitive people these phenomena led to mythical explanations, such as the work of fairies or giants.

Supposed Relation to the Flood. — When more thoughtful attention was given to the explanation of the erratic boulders and the associated deposits, the Biblical Deluge was adopted as the transporting power; and when it became evident that even this could not propel huge boulders so far, nor make the striæ on the pebbles, boulders, and bed rock, much less deposit the clay and stones side by side, it was supposed that the Deluge swept along with it great icebergs. Much controversy arose over this theory, embittered by the theological element involved. Even before the glacial theory was proposed, difficulties began to appear, so that when Agassiz proposed the glacial theory there were some who were ready to consider its possibility, though it was not without a bitter fight that its acceptance became general. How to obtain such a quantity of ice to float, how to make it pick up rock fragments from a valley bottom and carry them to the top of a neighbouring hill, how to account for the formation of long parallel grooves in the rock by swirling water currents, were difficulties that helped in the abandonment of the iceberg theory. And with the discovery of the belts of lateral moraines, of the phenomena of ice erosion, and a multitude of other features, the glacial theory has become well founded, for it explains all the features, which no other explanation can.

Agassiz's Explanation. — The glacial theory, now universally accepted as demonstrated, was a theory which naturally had its birth in a region of living glaciers. The goat herders of the Alps recognized the fact that the glaciers had formerly been more extensive, for they observed the same phenomena both at the glacial fronts and on the valley slopes and bottoms at a distance. Scientific men before Agassiz recognized the evidence of former extensive glaciers, but it remained for Agassiz to extend the theory to regions outside the Alps, and to postulate ice sheets for extensive areas in Europe and America where there are now no glaciers. This was brilliant generalization. Agassiz made the mistake of over-enthusiasm, for he eventually applied the theory even to Brazil.

Extent of the Glaciation

The Scandinavian Ice Sheet. — At first it was thought that the glaciation encircled the poles and spread out from polar centres, as the Antarctic Glacier does to-day. But this has now been found to be incorrect. In Europe the great centre of glaciation was Scandinavia, which was covered with an ice sheet that spread into Russia, Germany, Holland, and the North Sea. It was 1500 feet thick at the Hartz Mountains and perhaps 6000 to 7000 feet in Scandinavia. It covered an area of about 770,000 square miles and coalesced with an ice sheet, probably 4000 to 5000 feet thick, which developed on the British Isles. Northward and westward the ice reached into the Arctic and Atlantic oceans. The centre of this Scandinavian, or Baltic, Ice Sheet was in Sweden, a little east of the highland of Norway, rather than on the highest part of the upland (Fig. 170).

Mountain Glaciers of Europe. — At the same time the mountains of Europe were centres of glaciation, the Alps especially (Fig. 171). Glaciers filled all the Alpine valleys, spreading southward beyond the mountain base in Italy, and northward upon the plateau of Switzerland, southern Germany, and Austria, where it formed piedmont bulbs and piedmont glaciers. At the same time the Carpathians, Caucasus, Pyrenees, Apennines, and Urals had their expanded glaciers, and there were local ice tongues in the small mountains of Europe such as the Vosges, Black Forest, the Auvergne district of France, and the island of Corsica.

The Labrador and Keewatin Ice Sheets. — Apparently contemporaneous with the European ice sheet a continental glacier covered northeastern North America, occupying an area estimated as 4 million square miles. It had two main centres, one in Labrador, the other, the Keewatin, west of Hudson Bay. From these two areas, and perhaps one or more small centres such as Newfoundland, the ice spread outward in all directions, reaching southward into the United

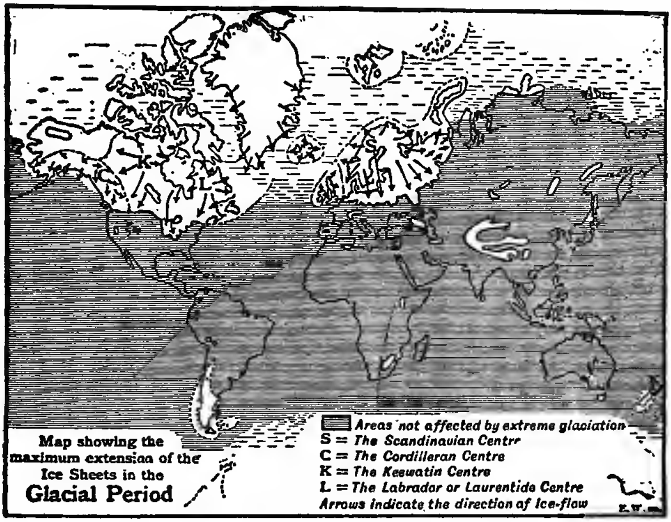


FIG. 170. — The world at the maximum of glaciation. Areas in Asia and South America much generalized. Glaciation in Alaska shown inaccurately, see Fig. 172. (After Encyclopædia Britannica.)

States to the islands south of New England, thence westward to the Ohio valley, then, crossing the Mississippi, the front swung northwestward, crossing into Canada near the Rocky Mountain front in western Montana (Fig. 172).

These great ice sheets were truly continental glaciers; and from Greenland we doubtless have a picture of the conditions that existed here during their existence. Apparently the snow accumulated until great ice caps developed, covering all the land, and spreading slowly outward from the centres of dispersion. How deep the ice was at the centres cannot be told; but since it was sufficient to propel the ice across the St. Lawrence valley and up the southern slopes of that valley, it must have had a great depth. The ice rose over the tops of Mt. Marcy in New York (5344 feet), Mt. Katahdin in Maine

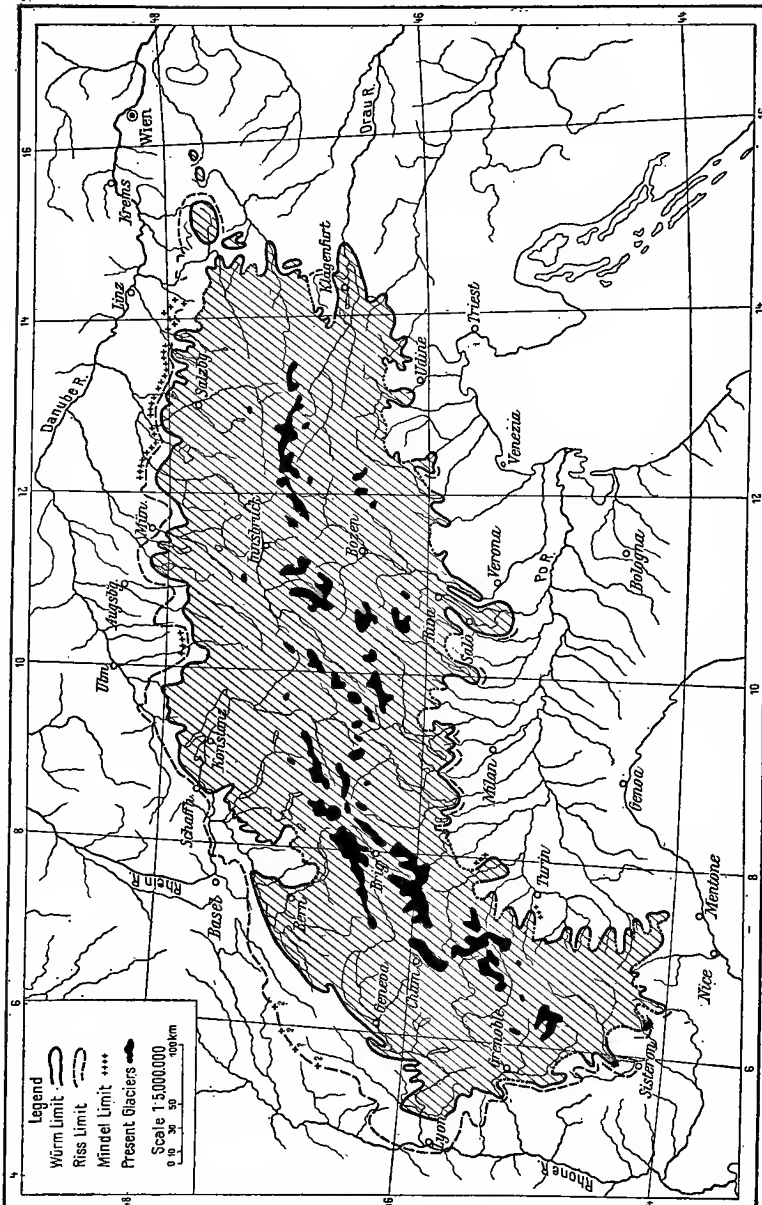


FIG. 171.—Maximum extent of glaciation in the Alps (oblique-lined area) compared with the present glaciers and snow fields (in black). Mindel and Riss represent older glaciations. (Leverett, after Penck and Brückner.)

FIG. 172.—Territory covered by the maximum extension of the glaciers in North America.

(5150 feet), and Mt. Washington in New Hampshire (6279 feet). To have reached such elevations the ice surface in the distant centre of dispersion must have been much higher. It may well have risen to an elevation of 10,000 feet.

Doubtless these ice sheets were vast deserts, as interior Greenland is to-day. Where they entered the sea they discharged icebergs. Where they terminated on the land they wasted away by ablation, and from their fronts huge torrents of sediment-laden water issued, for they extended southward into a temperate climate. How long the ice sheets lasted cannot be told, but from the work they performed the period of time must have been great.

Mountain Glaciers in Other Parts of the World. — Unless possibly in the Antarctic, there were no ice sheets comparable to these of North America and Europe in other parts of the world. Yet glaciers were more extensive than at present in many places in both hemispheres and even in places where there are now no glaciers. There were far more extensive valley and piedmont glaciers in Alaska, British Columbia, the Rocky Mountains, the Cascades and Sierra Nevada, the Andes as far as the southern tip of South America, New Zealand, the Himalayas, and other parts of the world. These were apparently true mountain glaciers, the greatly expanded ice mass of the North American Cordillera, for example, not being of such a nature as to be properly alluded to as an ice sheet, nor its source as a centre of glaciation. Within it, however, as in the present mountains of Alaska, there were innumerable centres of ice dispersion. The glaciers of the Antarctic, of Greenland, Iceland, Spitzbergen, and other islands of the Arctic extended farther than now. It cannot be asserted that this former extension of mountain glaciers was contemporaneous with the continental ice sheets of Europe and America, though there is no evidence that it was not.

FIG. 173. — Stand Rock in the Driftless Area of Wisconsin, a feature which could not possibly have persisted in glaciated territory. (After Salisbury and Atwood.)

Some Arctic Lands not Glaciated. — It is a curious fact that the great ice sheets were developed, not in the coldest regions of the present day, nor on land that is at present lofty. They occurred on two sides of the Atlantic Ocean; and elsewhere, excepting in the frigid zones, the extension of glaciers was confined to mountain regions.

In the mountains, however, there was no expansion of glaciers at all comparable to the ice sheets of Europe and North America. No ice sheets developed in Alaska or in Siberia, not even in the parts north of the Arctic Circle, though the mountains of Alaska and northeastern Asia both contained valley and piedmont glaciers of far greater size than at present (Figs. 170, 172).

The Driftless Area of the Mississippi Valley. — In the state of Wisconsin in the upper Mississippi valley and, to a smaller extent, in the adjacent states of Minnesota, Iowa, and Illinois is an area of over

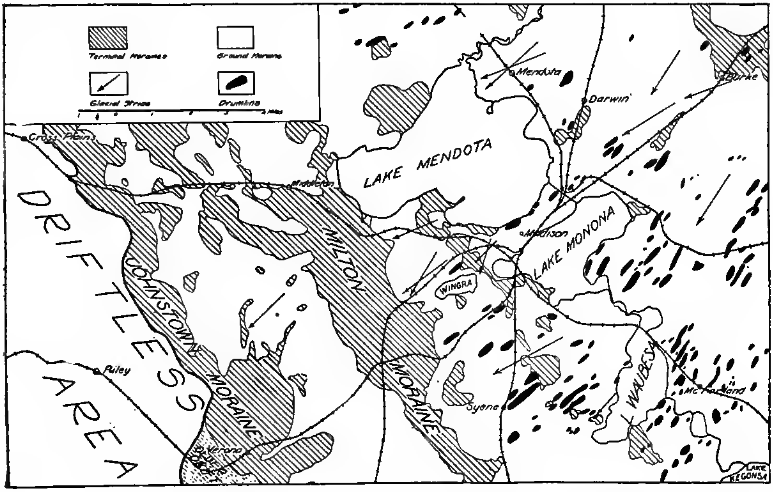


FIG. 174. — Part of the border of the Driftless Area in Wisconsin, with moraines and drumlins to the east. (After Alden and Thwaites.)

10,000 square miles which was not covered by the Labrador and Keewatin ice sheets of the continental glacier, between which it lay. It contains no glacial drift and is, therefore, known as the *Driftless Area*. The lobes of these ice sheets even coalesced south of the Driftless Area, and advanced over 300 miles farther south at the maximum of glaciation (Fig. 210).

It seems probable that the driftless character of this area is due to the temporary protection afforded by the highland of northern Wisconsin, in conjunction with the presence of the deep basin of Lake Superior north of it and the basin to the east now occupied by Lake Michigan. It is not driftless because of altitude, for it rises no higher than the adjacent land. If the period of expansion of the continental glacier had lasted longer, this Driftless Area would surely have been overridden (Figs. 173, 174).

Glacial Deposits

Deposits of Melting Ice and of Glacial Streams. — As in the case of existing glaciers, deposits were made by the vanished ice sheets,

Fig. 175. — The ground moraine or till sheet in Minnesota.

Fig. 176. — Boulder clay or till resting on solid rock, Vermilion iron range of Minnesota.

both directly by the ice and through the intervention of water. Thus we find both glacial deposits and glacio-fluviatile deposits. The latter are assorted and stratified, the former mainly unassorted mixtures of fragments of various sizes and kinds, without stratification. Very often the deposits consist of a mixture of the two, for ice and water were often working side by side. Some of these deposits were accumulated beneath the ice, still more were laid down at the front of the ice or beyond its front.

The Till Sheet. — Of the glacial deposits the *drift* or *till sheet* is by far the most extensive (Fig. 175). It consists of rock fragments dragged beneath the ice and carried in it, and left at the glacier front, where it had been brought when the ice melted. It may be classed as the ground moraine. Owing to its origin, the till consists of ground-up and partly ground-up rock fragments, the former being clay or rock flour, the other larger rock fragments up to the size of large boulders. These are mixed together, since they lay side by side in the ice (Fig. 176). The stones include a great variety of

FIG. 177. — View of stony fields and stone walls in Maine, showing the type of soil left in some places by the continental glacier. (J. Ritchie, Jr.)

kinds, gathered up from different rock outcrops over which the ice moved, and all mixed together. They are often polished and striated by the abrasion against one another in the differentially moving ice layers, and against the bed rock over which they were dragged. The bouldery nature of the till led to its being also called boulder clay; its compactness in places has given rise to the name *hard pan;* and its blue colour in unweathered outcrops has led to the name *blue clay.*

Composition of Till. — The till varies greatly in composition according to the kind of rock over which the ice bed passed, and the extent to which the rock has been ground up. Some till, derived from soft rocks, and subjected to thorough grinding, is mainly clay, though hard rock derived from more distant outcrops and not ground up may be scattered through it (Fig. 178). In central New York boulders of hard, crystalline rock, brought from Canada by the ice, and easily distinguished from the shale and sandstone rock of the region, are locally called "hardheads." In other places the ice mainly encountered resistant rocks, and these are less thoroughly ground up. This is true in many parts of New England, south of the Adirondack Mountains, in Wisconsin, and in various parts of Europe, as in Scotland. In such places till contains a smaller proportion of clay and far more boulders. Indeed, in places the surface may be so strewn with boulders that no agriculture is possible on the boulder-covered fields (Fig. 177).

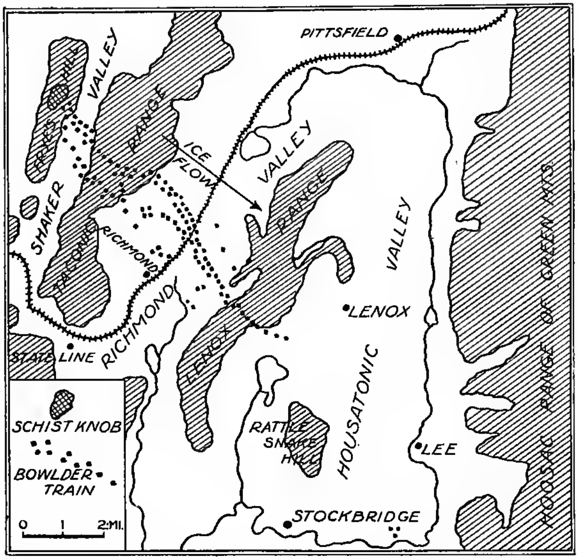


FIG. 178. — A boulder train, or deposit of glacial erratics of a distinctive and uncommon kind of rock, crossing three mountain ridges and valleys in western Massachusetts. (After Taylor.)

Thickness of Till. — The till sheet is variable in depth also. In some places the ice was heavily charged with rock fragments, notably where it passed over weak rocks, as in the states of the Mississippi valley. There the till is deep. Elsewhere the glacier had a small load, as in the regions of resistant rock like New England, the Adirondacks, northern Wisconsin, and east-central Canada. There the till sheet is thin, and there are areas of bare rock, but there are some areas of bare rock or thin drift which are due to the washing off of the ground moraine by glacial streams or rain-born rills of the closing stages of the Glacial Period when vegetation was still absent and erosion correspondingly rapid.

The irregular distribution of the till is dependent also on the movement of the ice. Where it was moving vigorously it carried the rock fragments away, and where its motion decreased they were accumulated beneath the ice. This is often seen on a small scale where a tail of boulder clay has accumulated on the lee side of a crag, giving rise to the phenomenon of *crag and tail*. It is also seen where till has been dragged into valleys transverse to the direction of ice motion.

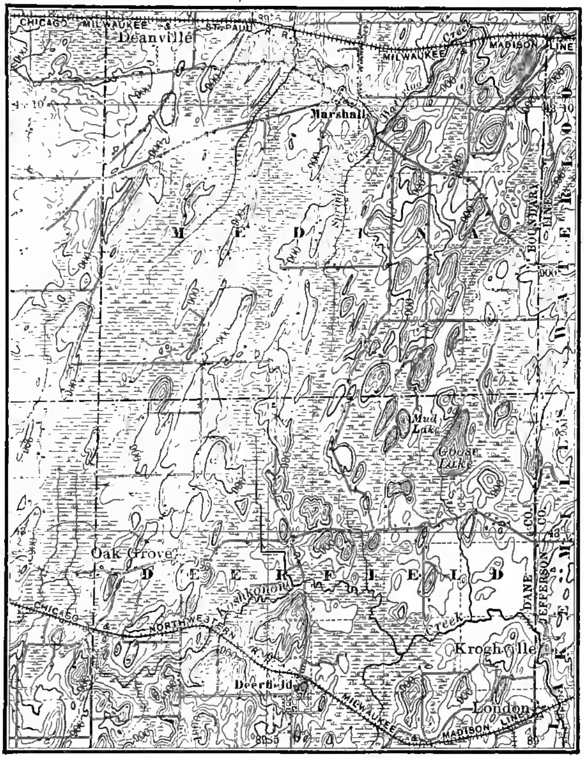


FIG. 179. — Topographic map of drumlins in Wisconsin. (Sun Prairie Quadrangle, U. S. Geol. Survey.)

On a much larger scale it is illustrated by the deep sheet of till in the Mississippi valley, where the ice spread out with slow motion. The lower ice layers can be overburdened just as certainly as a river can be.

Speaking generally, the till mantles the rock surface with a sheet varying in thickness from place to place, roughly parallel to the rock topography. It is not exactly parallel, however, for there are undulations due to irregularity of deposit, or to sculpture subsequent to deposition.

Drumlins. — Of these irregularities the most notable are the peculiar forms known as *drumlins*. These are oval hills sometimes occurring singly, but usually in clusters, and in the latter case the surface rises and falls in a series of billowy curves like the waves of the ocean. While the oval is the characteristic form, there are ridge-shaped drumlins, and there are double curves, and other variations in form. In all cases the long axis is in the direction of ice motion, and the end pointing toward the source of the ice, the stoss end, is steeper than the opposite or lee end. The drumlins vary in size, some being but a few hundred feet long and a few yards high, while others are a mile in length and 100 to 200 feet high. Perhaps a normal size may be given as a half mile long, an eighth of a mile wide, and

FIG. 180. — Longitudinal profile of a drumlin in Massachusetts. (J. L. Gardner.)

150 feet high at the highest point; but there are wide variations from this (Figs. 179, 180).

Distribution of Drumlins. — Drumlin clusters form a landscape of such a characteristic kind that they can be easily recognized on a map. There are such clusters in many places, some of the best known being in eastern Wisconsin; in central New York on the Ontario plain between Rochester and Syracuse, and north of this on the Canadian side of Lake Ontario; in the Connecticut valley; and in eastern Massachusetts and southern New Hampshire. Boston is built partly on drumlins, and drumlins make the islands of Boston Harbour, as well as the State House hill and Bunker Hill. Drumlins occur in great numbers in the lowlands of central Ireland, whence the name comes; they also occur in the lowlands of Scotland, on the North German plain, and elsewhere in Europe. In some of these clusters there are hundreds of individual drumlins.

Origin of Drumlins. — There are two theories for the origin of drumlins: (1) that they are irregularities built up beneath the ice by irregular deposit, as sand bars are built in an overburdened river, (2) that they have been carved out of a sheet of till, at first deposited fairly uniformly, and later sculptured — being a phase of roches moutonnées carved in a till sheet. It has not been demonstrated which of these explanations is the correct one, and it is quite possible that one theory is correct for some cases, the other for others.

Moraines. — When the ice halted for a long enough time, morainic deposits accumulated at the margin of the ice sheet, forming a terminal

Fig. 181. — Moraines in Finland. Eskers at right angles to them and abundant lakes inside the morainic border. (Hobbs, after Sederholm.)

moraine. The conditions involved in the accumulation of the moraine were complex and variable, including (*a*) the sliding down of débris from the front of the ice, (*b*) the dragging up and accumulation of débris beneath the thin edge of the ice, (*c*) the deposit by glacial water along the ice margin, (*d*) oscillation of the ice margin, (*e*) burial of ice blocks and thin glacier margins, and (*f*) the influence of preglacial topography. With the ever varying combinations of these factors the terminal moraine has been given great complexity and variety of form, composition, and depth.

Form of Moraines. — A terminal moraine may be but a few feet high and a few yards broad, or it may be several hundred feet thick

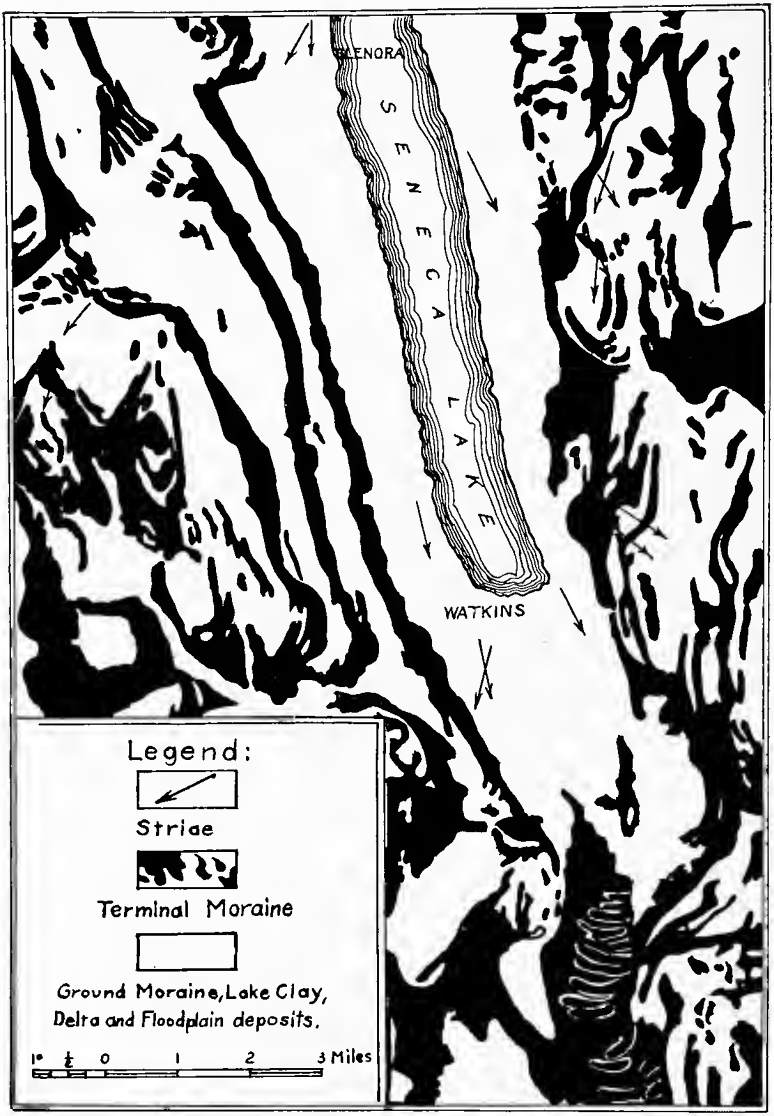


FIG. 182.—Lateral and terminal moraines in central New York.

and several miles broad; it may be a single, continuous belt or a series of separate or overlapping ridges. In form the moraine may be a ridge, or a complex of low undulating hills (Fig. 191). Most characteristically it has the *knob-and-basin topography*, consisting of hillocks or hummocks with intervening kettle-shaped depressions in the bottoms of which small ponds and swamps often lie. The hummocks may rise one or two hundred feet above the kettle bottoms, or the difference in elevation may be only a few feet. There is no rule, and seemingly no system, for the conditions during formation were most complex and variable (Figs. 181, 182).

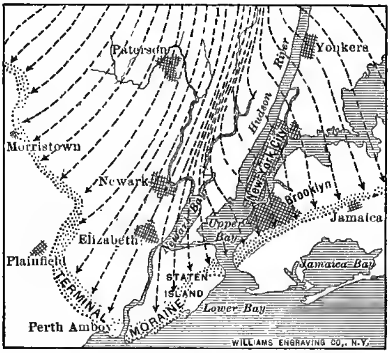


Fig. 183. — The glacial lobe near New York. (Salisbury.)

Composition of Moraines. — In composition a given part of the moraine may be all till, or all sand, or gravel, or clay, or, what is more common, it may consist of a mixture of two or all of these. The composition is as variable as the form. Very commonly there are

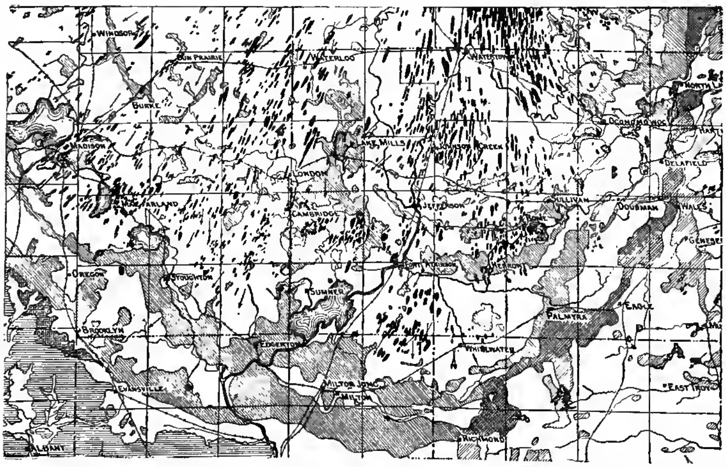


Fig. 184. — Moraines in southeastern Wisconsin (oblique lines); interlobate moraine near Richmond, Palmyra, and Delafield (cross-hatched); drumlins (solid black); striæ shown by arrows; older drift (horizontal lines) near Evansville and Albany; ground moraine and outwash in white. (After Alden.)

many boulders in the moraine, far more than in the ground moraine. This is because boulders within the ice were brought up to the front and there left in the accumulating deposits, and, therefore, far more would thus be concentrated along the frontal belt than existed in any single part of the ice. The terminal moraine is often a belt of boulder-dotted hills in a region where boulders are elsewhere rare. Sometimes so many boulders are accumulated that the surface is literally covered with boulder piles. The *bear den moraine* is the extreme of this condition, for here the boulders are piled one on the other, and over considerable areas no soil appears.

Moraines Bordering Glacial Lobes. — The terminal moraine marks essentially the position where the ice front stood for some time. From it, therefore, the form of the ice margin can be determined. The moraine clearly proves that the ice pushed its front forward in a series of lobes where valleys gave freer opportunity for movement, or where, for other reasons, the strength of flow was increased. As a result of this fact the terminal moraine sweeps in a series of lobes across the country, giving rise to the *lobate moraine*. Where the lobes coalesce there is often a band of *interlobate moraine*, where the terminal moraines of the two lobes unite to form a single band at the junction of the ice lobes (Fig. 184).

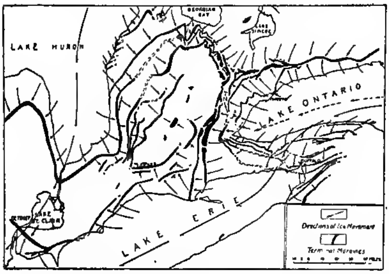


FIG. 185. — Recessional moraines in Ontario. (Taylor.)

Recessional Moraines. — When the ice advanced over the country it doubtless halted here and there and built moraines; but later, being overridden by the ice, these were erased. At its outermost stand a terminal moraine was built (Figs. 174, 183). Then, as the ice sheet began to melt away, and the front of the glacier receded to more and more northerly positions, there were periods of halting during which, of course, morainic deposits began to accumulate at the ice margin. Some of these halts gave rise to well-defined belts of *recessional moraine*, which are in no way different from the outermost terminal moraine excepting in position (Figs. 185, 186).

Glacio-Fluviatile Deposits. — If from small living glaciers great torrents of sediment-burdened water issue, it is to be expected that similar, or greater, torrents should have issued from the margin of the continental glaciers. That this was the case is abundantly proved by the glacio-fluviatile deposits, not only on the outer side of the terminal moraine, but all over the land across which the front of the melting ice sheets receded. These water-laid deposits vary greatly in character, and some are of such indefinite nature that it is difficult to state their origin; but there are some deposits of such definite form that their origin is not difficult to understand. All such deposits were formerly alluded to as "modified drift."

Eskers. — Among these one of the most striking forms is the *esker*, a long, winding ridge of gravel or sand, in some cases two or three hundred feet high, and very often 5, 10, or 15 miles long, and sometimes even much longer; but they are rarely more than a few

FIG. 186. — Recessional moraines between Wisconsin and New York. (After Taylor and Leverett.)

hundred yards broad at the base. Their tops may be even, like a railway embankment, or they may be undulating; and the course is commonly notably serpentine. In fact they were formerly called *serpent kames* in America, but now the Irish name esker is generally adopted, though the Swedish name *osar* is sometimes used. They are very common in regions of former glaciation, especially in hilly districts (Figs. 181, 187).

Cause of Eskers. — The esker is a deposit in a glacial tunnel, usually, if not always, at the base of the ice. Here the water flows with great velocity, often under head, and confined in a tunnel. It is often able to carry even good-sized cobblestones, and these are rapidly rounded in the swift current. If more load is given than the stream can carry, or if it is forced to build up its bed by the upward growth of an alluvial fan at the outlet of the tunnel, some of the coarser material must be laid down on the subglacial stream bed, the stream at the same time enlarging its tunnel by melting the roof. Thus a long, narrow, winding deposit of gravel is made, with ice roof, and ice walls. When the stream ceases to flow and the ice walls melt away, the gravel slides into a state of repose and the embankment-like esker is formed (Fig. 188). Under the conditions of its formation it is naturally given a rough stratification.

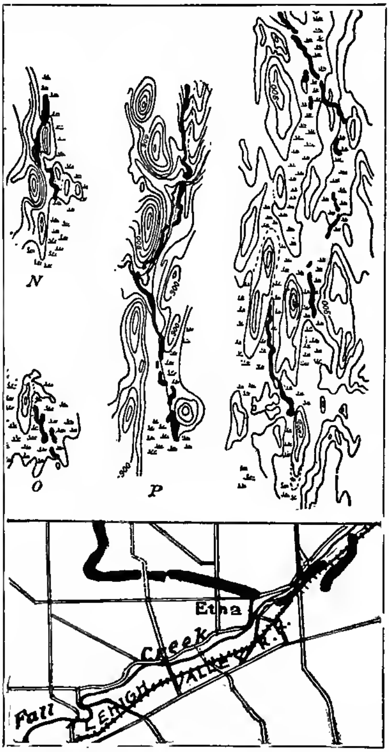


FIG. 187. — Maps of eskers (black) in Wisconsin and in New York. (Upper map after Alden.)

Eskers cannot develop, at least not in a very perfect form, in ice that has much movement, for the tunnels would soon be closed. Nor can they develop at the base of a thick ice sheet, for the pressure would close the cavity. The most favourable position for esker development is under the thin, stagnant front of a glacier, or beneath a detached ice block, conditions that were common along the front of the receding ice sheets. Doubtless also esker development is favoured along the margins of valley glaciers, or glacier lobes, where the ice is thin, the motion slight, and the volume of water great. It is from such places that glacial torrents issue from living glaciers, and doubtless eskers are forming in some of them, as, for example, in Alaska, where small eskers are found on ground from which the glaciers have receded within a century.

Kames. — Hummocky deposits of sand and gravel, often with perfect stratification, are called *kames*. There seem to be various conditions under which kames can develop, all depending upon the transportation of coarse sediment by glacial streams. Some kames may form beneath the glacier where surface streams fall through moulins, though the more common result of such a fall is the excavation of a pot hole. If, however, the stream bears much sediment, it may accumulate in a hummocky kame deposit.

An esker often merges into a kame area; and, after a certain distance, the esker form again develops. In this case it is evident that the kame is formed beneath the ice, and the conditions are apparently the enlargement of the subglacial cavity and the irregular deposition of the sand or gravel in which are incorporated blocks of ice from the roof of the tunnel, whose later melting forms depressions in the gravel.

FIG. 188. — Esker near Yakutat Bay, Alaska.

Other kames were formed along the margin of the glacier where gravel came to rest on the edge of the ice, or on detached stagnant blocks. Later melting of the ice gave rise to kettles and hummocks. This process is seen in course of development along the fronts of some of the Alaskan glaciers. Patches of kame form parts of many moraines left by the continental glaciers, and in some cases there are extensive areas of this type of moraine which has been called *kame moraine*, or *kettle moraine*.

Esker Deltas. — When a glacial stream, on emerging from its ice tunnel, enters a lake, it builds a delta with the load of sediment that

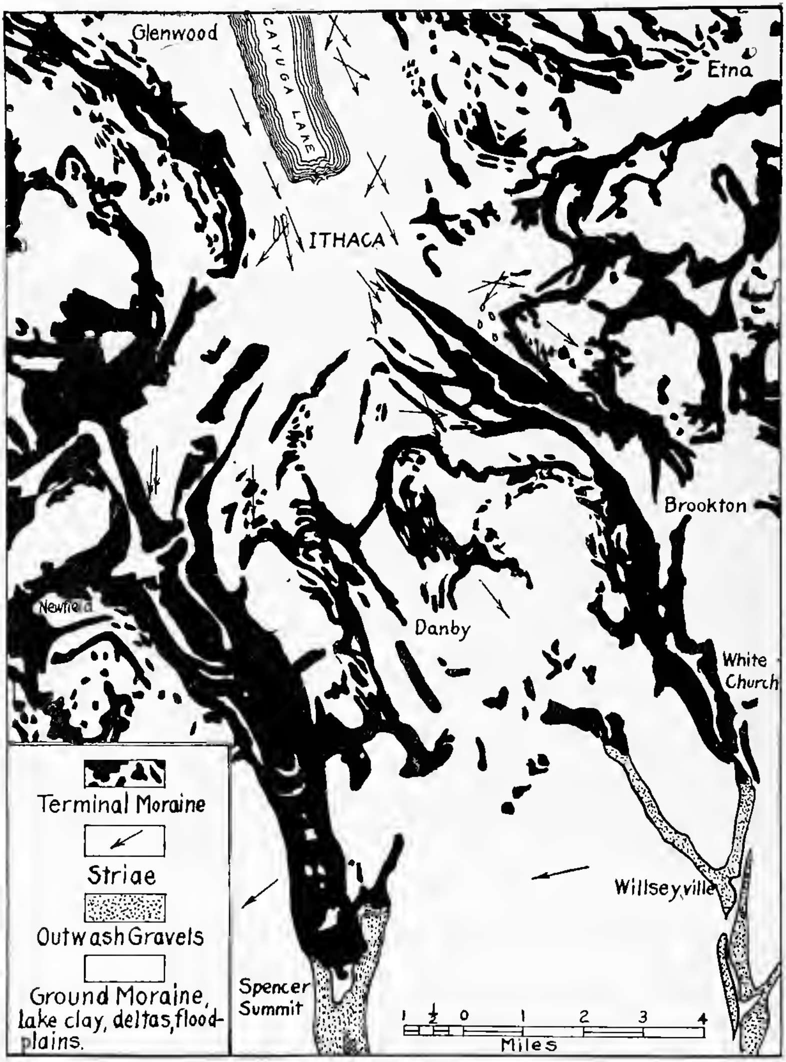


FIG. 189.—Terminal moraines and valley trains of outwash gravel in central New York.

it carries. Lakes were often developed in such positions along the front of the continental glacier, where the ice formed a dam across a valley sloping toward it. With the disappearance of the ice dam the lake is drained, but the delta remains, and if an esker was built in the ice tunnel, it will be seen extending up to the delta. Such an esker-fed delta may be called an *esker delta*, though it has been given the less descriptive name *sand plain* in New England, where there are numerous perfect instances of this type of land form.

Outwash Gravel Plains. — Where the glacial streams issued upon a slope leading away from the ice, or where they made extensive enough deposits to grade up such a slope, outwash gravels were accumulated, as they are in front of living glaciers. On open land these outwash gravels are in the form of great, coalescing alluvial fans or outwash aprons. Southern Long Island was built up by such outwash gravel deposits during the Glacial Period, just as such accumulations are being formed around the margin of the Malaspina Glacier to-day; but where the streams were confined in valleys, they aggraded the valley, making a flat valley floor of gravel. It is to such

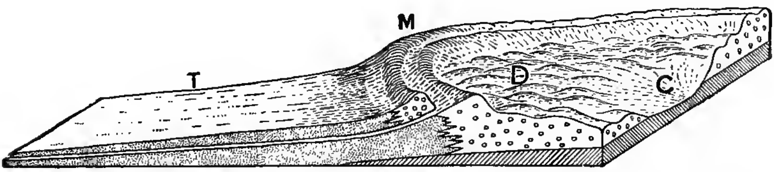


FIG. 190.—Diagram to show relationships of outwash, *T*, to moraines, *M*. (After Penck.)

narrow, outwash gravel plains that the name *valley train* is most appropriately applied (Figs. 189, 192). The ice-born streams carried their deposits great distances beyond the ice front, from southern Illinois far down the Mississippi, for example.

On the surfaces of outwash gravel deposits the old courses of the braided streams may still be traced, and the well-rounded pebbles testify to the rapid motion of the streams that brought them. Such plains are often pitted with little kettles; and some good-sized ones, where buried ice and stagnant ice blocks have melted out and allowed the gravels to settle. Swamps, ponds, and small lakes occupy some of these kettles.

Near the point of emergence of the glacial stream, the outwash gravel plain consists of coarse fragments, and it is often cut into terraces by the rapid erosion of the stream. The very smooth river-laid part of the outwash gravel plain grades into a hummocky kame topography, where the gravels were deposited on the ice, whose later melting has given rise to the kame topography. In such places the outwash gravel and moraine merge imperceptibly into one another, a condition which finds expression in the term *moraine-headed terraces*.

Loess of the Glacial Period. — Among the fine-grained deposits of the Glacial Period are thick deposits of loess. In the United States they are especially well developed in the Mississippi valley. The origin of this loess, whose character is discussed in the chapter on the work of the wind (pp. 72–73), is not agreed, but it seems probable that some

FIG. 191. — Hummocky recessional moraine in central New York.

FIG. 192. — Valley train of outwash gravels near upper view.

of it is wind-laid and some water-laid. Just after the Glacial Period, when grass and trees had not yet readvanced over the glaciated lands, the wind must have been supplied with great quantities of fine-grained dust, especially on the outwash plains and valley trains.

Marginal Lakes

Ice-dammed Lakes. — A continental glacier, covering all the land, has along its front some valleys sloping away from it, some toward

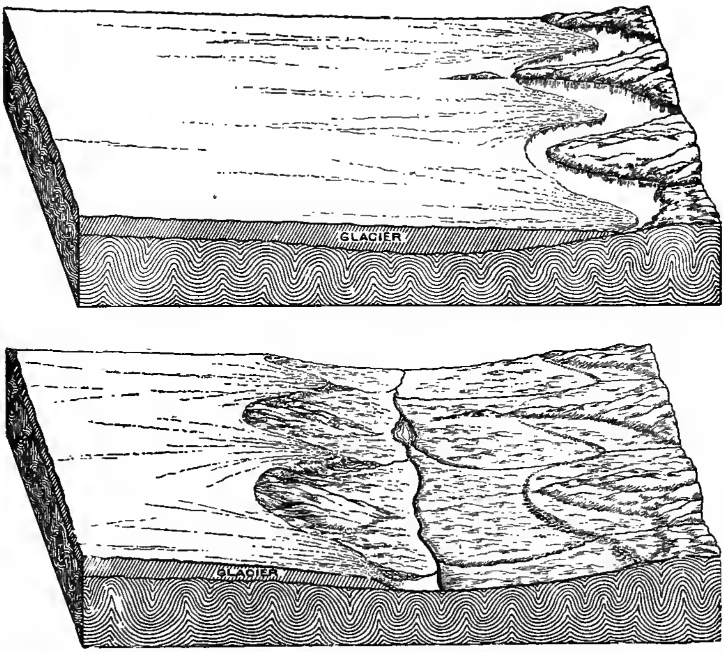


Fig. 193. — Two stages in the recession of the continental glacier in a hilly region. Upper diagram with ice-dammed lakes, lower with valley drainage developed between the glacier and the terminal moraine of the previous stand.

it. In the latter case, water naturally accumulates (Fig. 193) in a lake with an ice dam and an outflow across the lowest point in the rim. Lakes of this origin abounded along the front of the ice sheets of both Europe and America, during all stages in their recession. Some of them were very small in size and quickly filled with deposits; others were so large, or existed for so short a time, that the deposits in them were not noteworthy. Sometimes their outlets fluctuated greatly as the ice front advanced or receded. Through the outlets of the great temporary lakes, large volumes of water flowed and cut broad channels in drift or rock, where now no water flows (Fig. 194). This is illustrated along the divide between Sweden and Norway, where there are broad outflow channels, some of them sunk into the mountain

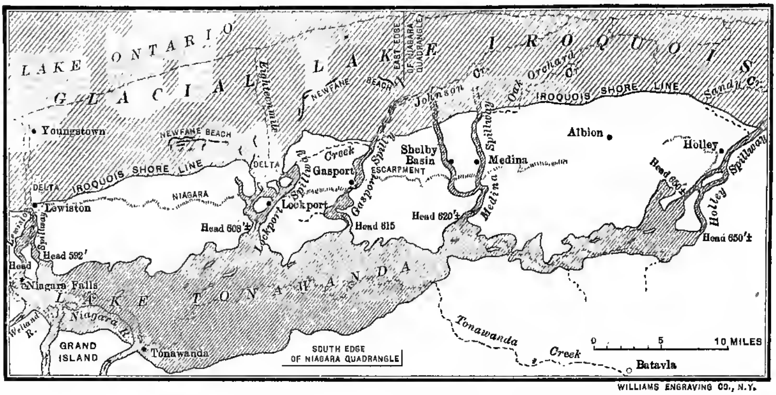


FIG. 194.— Glacial Lakes Tonawanda and Iroquois with the five spillways, of which the Niagara Spillway at Lewiston was lowest and, therefore, persisted. (Taylor.)

rock by the water that flowed westward from lakes held up between the ice sheet in Sweden and the Norwegian mountain divide.

Features made by Marginal Lakes. — The former presence of such lakes is clearly proved by a number of phenomena, notably (*a*) the outflow channels, (*b*) beaches along the abandoned lake shores, (*c*) deltas where tributary streams entered the temporary lakes, but now perched upon the hill slope and often dissected by the stream that built them, (*d*) a sheet of lake clay (Fig. 195) on the bottom of the

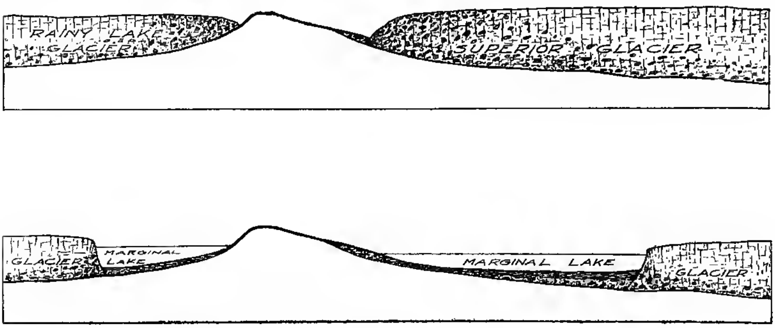


FIG. 195.— Diagram to explain superposition of lake clay upon unstratified till.

extinct lake, (*e*) occasional iceberg deposits, where floating ice in the lake became stranded and, on melting, dropped some of the load of débris that it carried, especially boulders.

Glacial Lake Agassiz. — Among the many temporary lakes marginal to the ice sheet of North America one of the most noteworthy was that that developed in the northward-sloping valley of the Red River of the North, in North Dakota, Minnesota, and Canada. It started as a small lake with an overflow southward into the Mississippi, but as the ice dam melted back it grew in size until finally it had a length of about 700 miles, a maximum width of 250 miles, and an area of 110,000 square miles, or more than the combined area of all the Great Lakes. Lake Winnipeg and other smaller lakes lie in depressions in the bed of this great extinct *Lake Agassiz*, as it has been called (Fig. 196.)

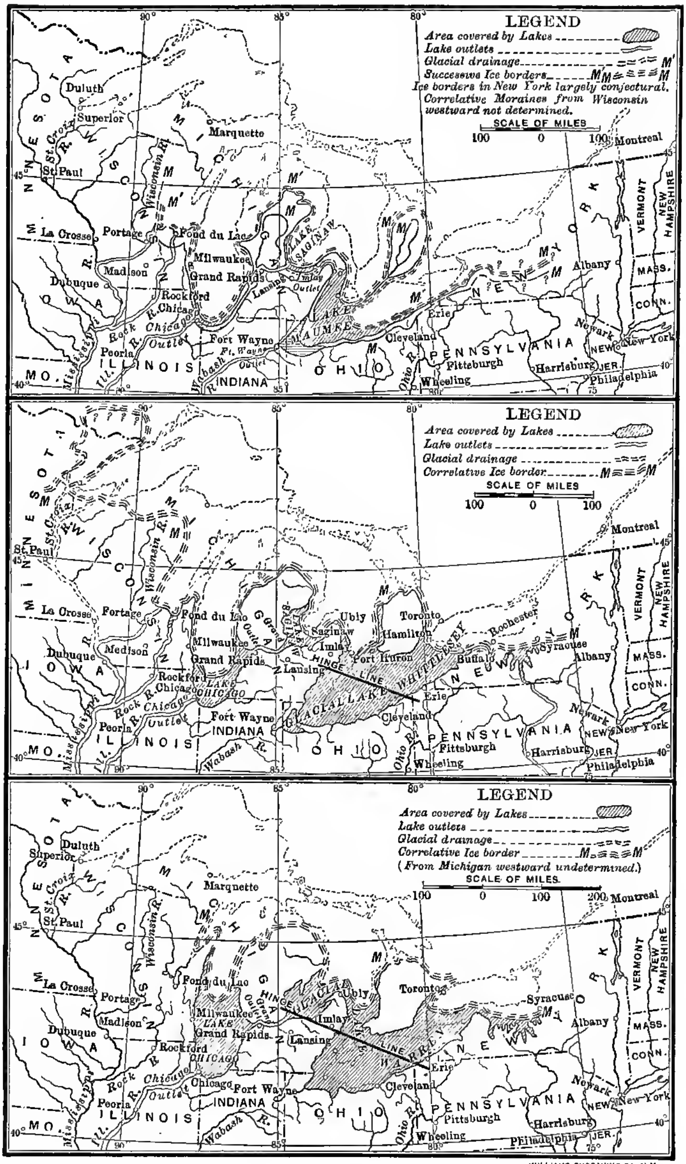
Lake Agassiz, though covering a great area, was shallow, and it received a vast quantity of sediment from the ice front. This, settling upon the flat bottom of the Red River valley, has given rise to a very level plain, of fine-grained silt, which is now the seat of extensive wheat cultivation. Beaches and deltas mark the border of this extinct lake, and its outflow channel is easily recognized.

Fig. 196. — Map to show area and position of maximum territory covered by various stages of Lake Agassiz. (After Upham.)

The Glacial Great Lakes. — The receding ice sheet also interfered with the Great Lakes-St. Lawrence drainage, for at first it occupied the entire basin, then, receding northeastward it lay as a dam across it. At first small lakes developed at the ends of the Great Lakes, and in other valleys sloping northwards. Then, as the ice receded, these grew larger, and one by one coalesced, until finally the ice disappeared from the St. Lawrence valley. The beaches and deltas of these lake stages have been carefully studied, and the various outflow channels have been identified.

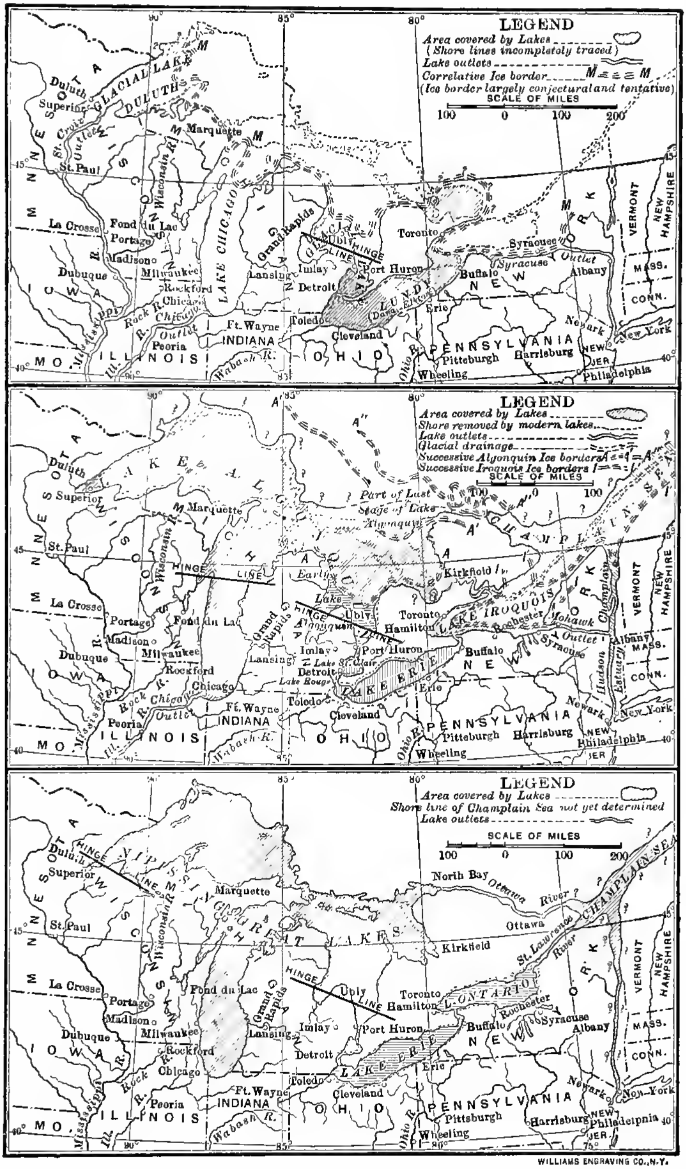
The history of the lake stages marginal to the receding glacier in the Great Lakes region has been complicated not merely by the recession of the ice, but also by the fact that the land has been rising. For this reason the three upper Great Lakes flowed into the St. Lawrence through the Ottawa River at one stage, and then the ocean waters reached up the St. Lawrence into Lake Ontario. Later uplift so tilted the land that the upper Great Lakes flowed out through the channel past Detroit. The maps (Figs. 197, 198, 200, 204), with descriptions beneath, state in sequence the main episodes in this complicated history of marginal lakes associated with ice recession from the Great Lakes region.

Some of the beaches of these lakes are so well developed that they were recognized as beaches before their cause was known. Such is



WILLIAMS ENGRAVING CO., N.Y.

Fig. 197. — The Glacial Great Lakes. Upper map shows an initial stage with independent bodies of water like Lakes Maumee and Chicago, which had separate outlets. Middle map has Lake Whittlesey draining into Lake Chicago. Lower map shows Glacial Finger Lakes draining westward into Lakes Warren and Chicago. Glacial Lake Duluth not shown in early stages because of incomplete information. (Taylor and Leverett.)



WILLIAMS ENGRAVING CO., N.Y.

FIG. 198.—The Glacial Great Lakes. Upper map shows Lakes Duluth, Chicago, and Lundy nearing the end of the Mississippi outlets. Middle map shows Lakes Algonquin and Iroquois and the Mohawk outlet, as well as the Kirkfield outlet which deprived Niagara of a large part of its water. Lower map shows the Nipissing Great Lakes and outlet into Ottawa River, which was subsequently abandoned for the present St. Lawrence outlet through uplift and tilting north of the *Hinge Lines*. (Taylor and Leverett.)

the Iroquois beach in New York south of Lake Ontario along which an Indian trail ran, and later a road, called the "ridge road." The silt deposited on the temporary lake bottoms has helped to level the surface and has made a fertile soil, the seat of fruit and other thriving agricultural industries.

Marginal Channels

Moraine Terraces. — Water flowing along the ice margin, and at times deflected from it, has in some places caused deposits which are morainic in their character. Some of these deposits form even-topped terraces, called *moraine terraces*. They are really aggraded, marginal, stream valleys with the ice for one wall, which, on melting away allowed the deposit to slide into an angle of repose, giving rise to the terrace face. In other portions of the marginal valleys lakes were developed and filled, giving rise to even broader terraces.

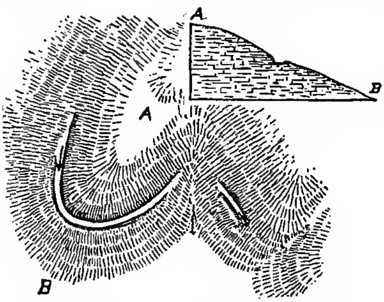


Fig. 199. — Map and profile of marginal channel at Slaterville Springs, N. Y. (Rich.)

Abandoned Marginal Gorges. — Some of the marginal streams, because of steeper slope, or less sediment load, cut into their beds instead of aggrading them; and some have aggraded in places and cut in others. Where the streams were able to erode their valley bottoms, marginal channels resulted, often as well-developed gorges. Some of these are still occupied by water, while some have none, or have streams far too small to have made the valleys in the bottoms of which they meander, cutting neither the bed nor the sides. Occasionally the marginal channels are to be found on the hill slopes in apparently unnatural positions, contouring the hillside instead of extending down the slope as gorge-forming streams normally do. Such a channel offers clear evidence of the presence of some retaining wall, such as an ice margin, along which the water flowed (Figs. 199, 201).

Marginal channels with the same characteristics exist along the borders of present-day glaciers, and they are to be expected wherever ice sheets have stood, especially in hilly regions. They abound in the glaciated region of Europe and America, and they, together with overflow channels, often serve as the site for roads and even for railways across divides. Associated with moraines, they are an aid to the determination of the position of the front of the receding continental glacier (Fig. 337).

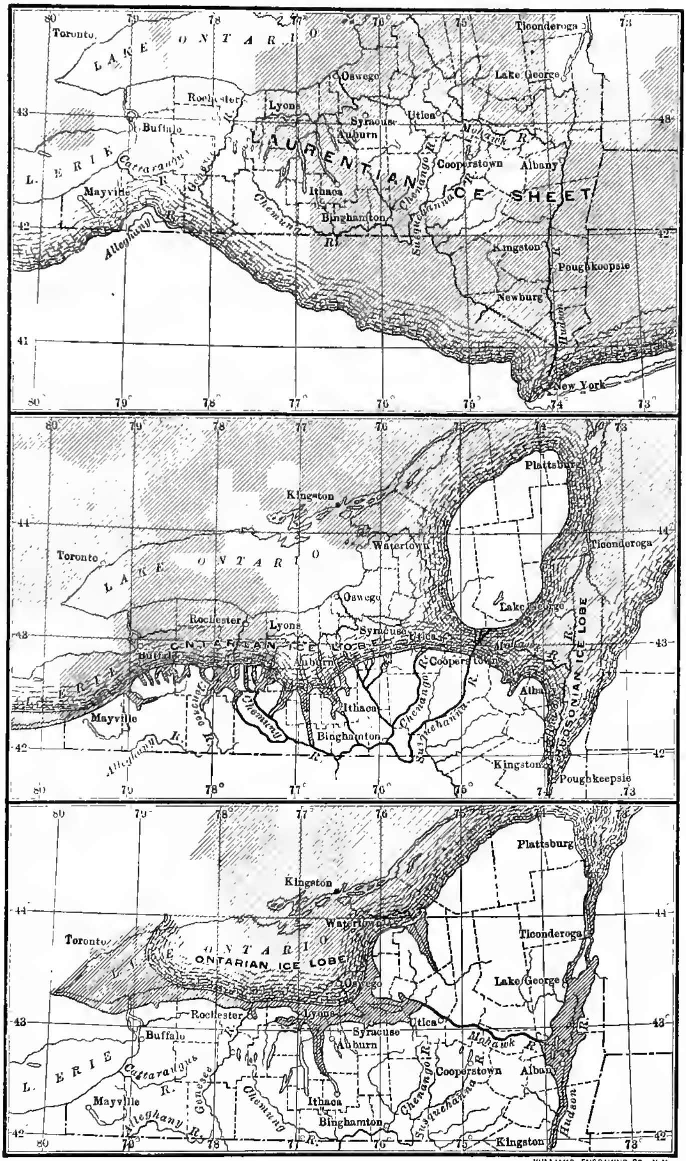


FIG. 200. — Three stages in the recession of the ice sheet from New York, showing glacial lakes and changing outlets. (Fairchild.)

Glacial Erosion

Moderate Erosion on Plains. — The presence of striæ on the bed rock and of roches moutonnées forms in the ledges, as well as the scratched stones and boulders that the glacier carried, testify to the fact that the continental glacier, like other glaciers, was an erosive agent (Fig. 202). Similar testimony is offered by the deposits of drift that the ice has left, for these materials were dragged from the surface over which the ice flowed. Yet the evidence is convincing that, in places, the glacier did little more than scrape off the products of preglacial weathering, and in places did not even accomplish this much. Probably the greater part of the land surface over which the ice sheets passed was lowered but little, though there is no means of estimating the exact amount.

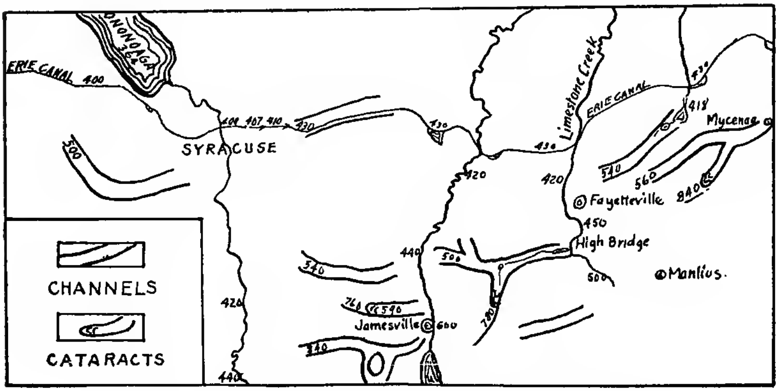
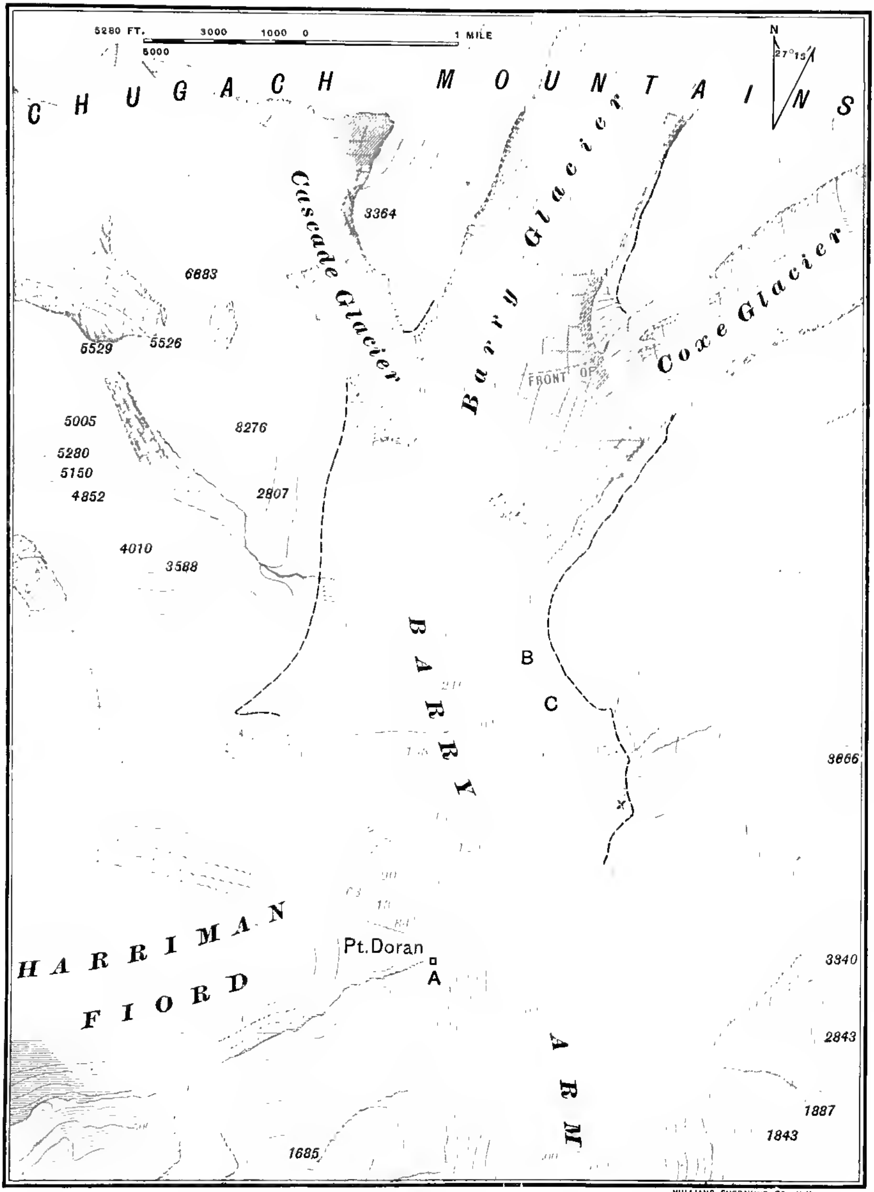


Fig. 201. — Marginal channels in central New York. (Fairchild.)

Profound Erosion in Valleys. — While of slight effectiveness in general, the ice sheet becomes a powerful agent of erosion locally. Wherever the topography tended to concentrate the ice flow, as along a valley, evidence of glacial scouring appears, and in some favourable localities there is convincing evidence of profound glacial erosion. This is well illustrated in the Finger Lake region of central New York. Here the upland was but little worn, and rock, decayed before the advance of the ice, was not all removed; but the north-south valleys, along which the ice flowed freely, were broadened and deepened, their slopes were steepened, the valley spurs were worn away, and the tributary valleys were left hanging. In other words, the same topographic features were developed as are found in Greenland, Alaska, Norway, Scotland, New Zealand, and other glaciated mountain lands. Throughout the region of former glaciation the same evidence is present and forms are found that no known agent of erosion excepting ice could produce (Fig. 203, Pls. V, IX).



HARRIMAN FIORD, ALASKA

A fiord due to glacial erosion in youthful mountains. Barry Glacier receded notably from 1910 to 1913, as observed by B. L. Johnson. In 1899 it terminated near Pt. Doran, where it built a moraine bar represented by the cross-hatched shoals, and extended as high as the heavy dotted line. The stream from the small ice tongue southwest of Cascade Glacier is in a hanging valley. (See Fig. 154.) Contour interval above and below sea level 100 feet. (From map by National Geographic Society's Alaskan Expedition of 1910, Lawrence Martin in charge.)

FIG. 202. — Glacial groove and striæ on Keweenaw Point, Michigan.

Rock Basins. — Ice erosion has deepened some valleys locally, forming *rock basins* in which lakes exist. Such are Lakes Cayuga and Seneca, two of the Finger Lakes. It is highly probable that a large portion of the depth of Lakes Ontario, Erie, Huron, Michigan, and Superior is due to glacial erosion, though upon this all are not agreed. Certainly many lakes lie in basins partly or wholly excavated by ice erosion. The formation of rock basins is due to (*a*) weak rock, and (*b*) differential erosion as a result of rapid flowage or thick ice.

FIG. 203. — Hanging valley near Michipicoten, Ontario.

The Formation of Lakes

The Abundance of Glacial Lakes. — The glaciated lands are dotted with lakes, varying in size from Lake Superior to small pools. There are said to be 10,000 lakes in Minnesota alone, and in Europe and America there are hundreds of thousands of lakes and ponds that have come into existence as a result of the glacial invasion. These lakes are of variable origin and often due to a combination of two or more causes.

Causes of Glacial Lakes. — Mention has just been made of the rock basin lakes, and the instances given — the Great Lakes, and the two Finger Lakes, are also partly due to drift deposit. Many lakes are due solely to this cause; for if a moraine, or an esker, or other glacial deposit has been laid down across a valley it serves as a dam until it is cut through by the outlet stream. Still another cause for lakes is the irregularity of the drift deposit itself, already spoken of in the description of moraines, kames, drumlins, and other deposits. In the depressions on such drift forms, ponds and lakes abound. Tens of thousands of them are present in the terminal and recessional moraines.

These are the three main classes of glacial lakes, but there are many variations according to the nature of the deposit, or the dam, or the topography. Some lakes are long and finger-like, when occupying a glacially sculptured valley. Such lakes abound in mountainous regions, as in Scotland, Norway, and the Alps, where Lakes Como and Maggiore are typical instances. Other lakes are circular, as is often the case with lakes in kettles. Still others are broadly branching, where the dam causes the water to spread over and partly submerge a low, hilly land, as is often the case in Maine, New Hampshire, the Lake Superior region, and Canada. There is infinite variety of form, size, and depth among the glacially formed lakes.

Lakes an Evidence of Youth. — The lakes caused by the ice sheet are necessarily youthful phenomena in the drainage systems that the glacial invasion has rejuvenated. They, together with other phenomena, testify to the recency of the retreat of the ice. Slowly they are being filled, and some have already been destroyed by filling or by the cutting down of the barrier, or by both processes combined. In the meantime they act as temporary baselevels to the streams above, checking the development of the rejuvenated streams.

Diversion of Streams

The Deep Burial of Preglacial Stream Courses. — The rejuvenation of the streams of the glaciated country has not only led to the development of lakes in their valleys, but also to numerous changes in stream courses. Sometimes the drift has been deposited so deeply as to quite effectually obscure the preglacial topography in regions

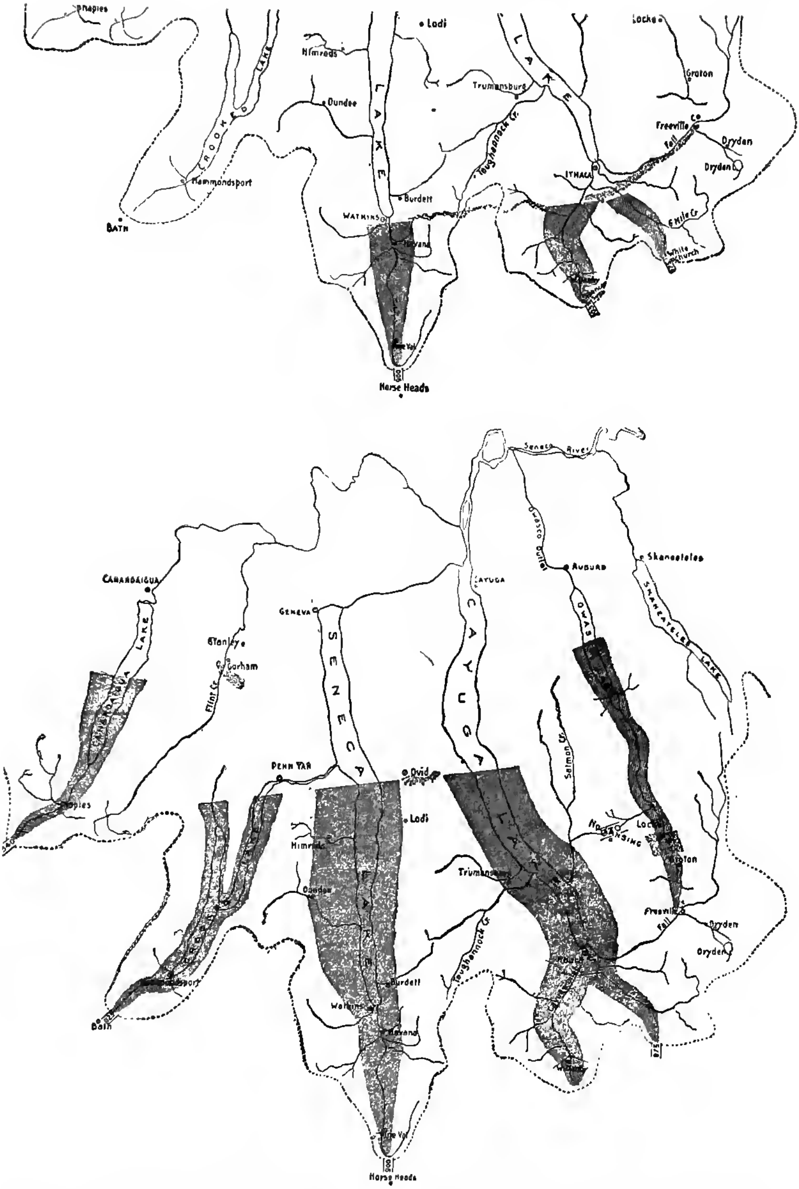


FIG. 204. — Lakes along the border of the continental glacier in central New York, showing coalescing of water bodies and occupation of lower outlets with northward retreat of the ice. (Watson.)

U

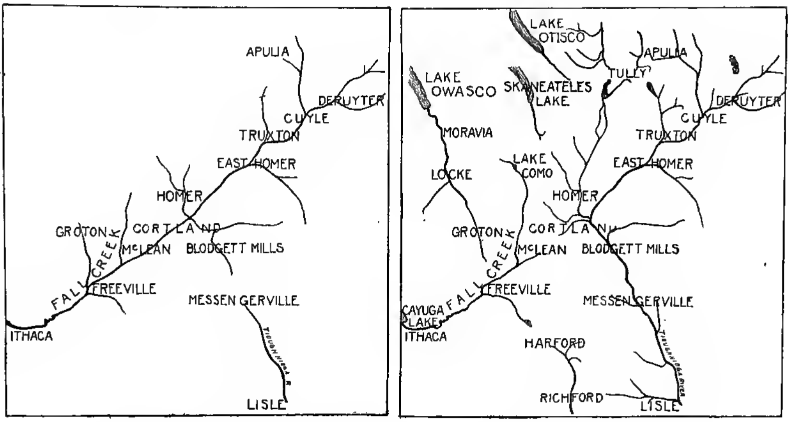


FIG. 205. — Preglacial and present drainage near Ithaca, N. Y. (Carney.)

of low relief. In the Middle West depths of 200 to 300 feet are recorded in the well borings, and it is estimated that on the lower peninsula of Michigan there is an average depth of 300 feet of glacial drift. On such surfaces an essentially new drainage system has developed, often along quite independent lines from those of the preglacial streams. The streams developing on such drift topography have the

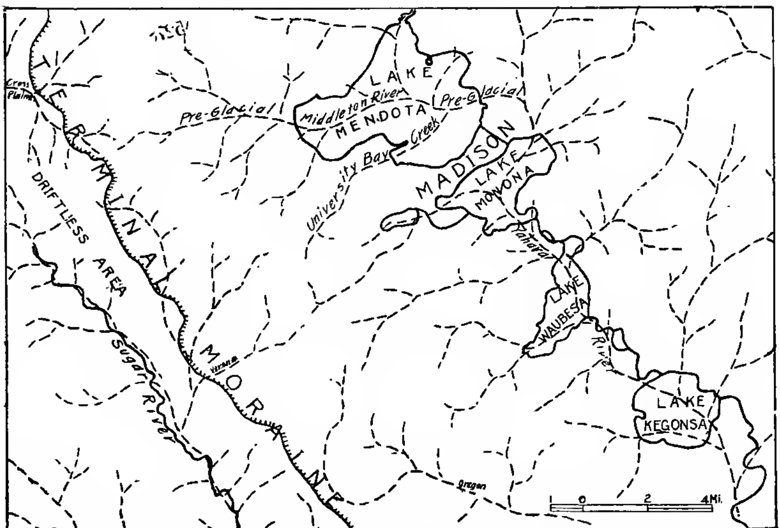


FIG. 206. — Map showing preglacial drainage (dotted lines) and present streams and lakes near Madison, Wisconsin. (Thwaites.)

features of youth — lakes, steep-sided valleys, imperfectly developed tributaries, and flat-topped divides. It was largely because of this youthful topography that extensive areas in the Central States were too swampy for tree growth, and were, accordingly, open prairies when first seen by white men.

Partial Burial of Stream Courses. — In other cases, and especially in hilly regions, drift deposits have led to local diversion of stream courses. There are many conditions under which such diversion has been brought about. For instance, deposits in a stream valley have buried projecting rock spurs, and the streams, flowing in these deposits after the ice disappeared, and cutting into them, have been superimposed on the buried rock ledges to one side of the axis of the preglacial valley. Again, drift deposits have turned streams out of their valleys and forced them along new courses for a part or whole of their length. In some of the valleys of New York the drift is 200 or 300 feet thick (Figs. 205, 206).

Reversal of Drainage. — Still another case is where valleys which, before the ice came, sloped northward, are now occupied by south-flowing streams, thus completely reversing the direction of stream flow. Such reversal has been brought about by a combination of processes such as (*a*) lowering of divides by glacial erosion, (*b*) lowering of divides by the erosion of glacial waters, (*c*) deposit of sediment in lake and stream bed, thus grading up a slope away from the ice, and (*d*) tilting of the land. In this way profound changes in drainage have been brought about. The St. Lawrence drainage has lost heavily by this process, many tributaries that formerly flowed northward having been turned into the Susquehanna and Mississippi systems. The entire headwaters of the Ohio, for example, above Cincinnati are apparently normally north-flowing, having had their course inverted by the effect of glaciation (Fig. 207).

Establishment of New Stream Systems. — Through the effects of glaciation the drainage has been completely rearranged in places, elsewhere slightly modified. Niagara River did not exist, at least not along its present course, before the Glacial Period; nor did the St. Lawrence system, which is apparently made by the union of several streams, some tributary to Hudson Bay, some to the Mississippi, some to the Gulf of St. Lawrence. It is a composite river system with a combination of features of youth and inherited maturity. In the more hilly and mountainous regions the rivers have been less completely changed, though often locally diverted; in the less hilly regions, like the Mississippi valley, many completely new courses have been established.

Postglacial Gorges and Waterfalls. — With all this rejuvenation the streams have naturally set to work upon their task of establishing themselves in their new condition. Thus they are at work toward the establishment of grade. In this process they have excavated gorges, as at Niagara and hundreds of other instances, and in excavat-

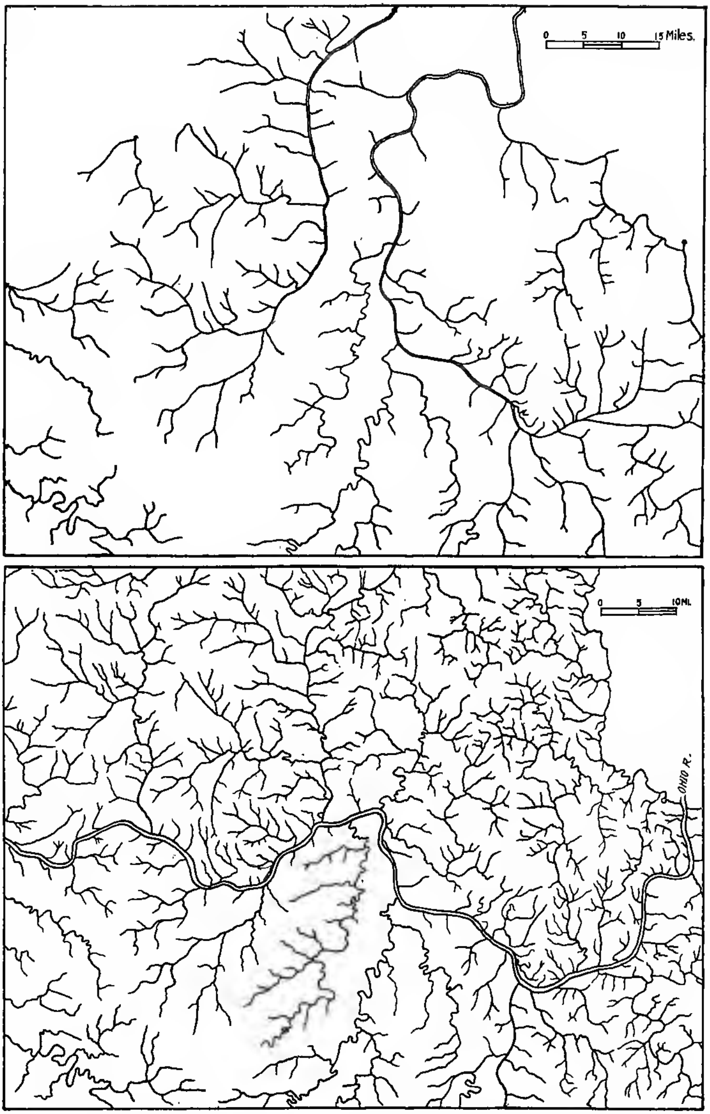


FIG. 207. — Preglacial north-flowing drainage (above) and present west-flowing Ohio drainage in the eastern part of the state of Ohio. (Tight.)

ing them they have developed a still greater number of waterfalls. Thus postglacial gorges and waterfalls characterize the region of recent glaciation because the streams that have been rejuvenated as a result of the glaciation have not yet had time in most cases to cut their valleys down to grade (Fig. 208).

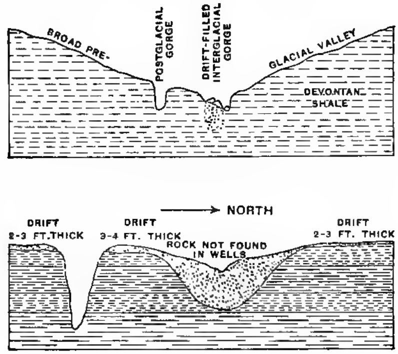


FIG. 208. — Postglacial and interglacial gorges near Ithaca, N. Y.

Gorges in Hanging Valleys. — Among the causes for gorges and waterfalls is the change in slope which many tributary streams find in passing out of their hanging valleys to the main valley bottom. This is well illustrated in the Finger Lake valleys of central New York, notably Seneca and Cayuga, where scores of tributary streams, flowing through mature valleys in the uplands, have an abrupt change of slope as they near the main valleys, and descend in precipitous courses through narrow, deep gorges, in the bottoms of which the streams leap from ledge to ledge in a series of rapids and falls (Figs. 60, 76). This condition is also illustrated in the English Lake District, in the Scottish Highlands, in Norway, and in all other regions where glacial erosion has lowered the valleys through which the ice flowed freely.

INFLUENCE OF GLACIATION ON TOPOGRAPHY

Changes not Revolutionary. — Throughout this chapter instances have been given of the influence of glacial action on the topography, and enough has been said to show that it has been profound. Yet the impression must not be gained that this influence has, in general, been revolutionary, for it is true that, in the main, the general topography is much as it was before the ice came. Large sections have been modified only in detail.

Erosion Generally Superficial. — The modification of topography has been brought about (*a*) by erosion, (*b*) by deposition. Erosion, as already stated, has worked locally, greatly changing the topography of mountain regions by the deepening of valleys and by cirque recession, and elsewhere broadening and deepening valleys through which the ice flowed freely. But over the larger part of the area in United States covered by the continental glacier the effect of glacial erosion has been somewhat superficial. In Canada, however, and especially in the region near Lake Superior, Hudson Bay, and Labrador the continental glacier swept away all the soil from broad areas of resistant rock, leaving much naked upland, drift only in the valleys, and there very stony drift, and many rock basins now occupied by lakes.

Deposition on Uplands. — Deposition has also produced unequal effects. Over much the larger part of the area covered, there is only a thin veneer of till on the hillsides and hilltops, scarcely obscuring the natural rock topography, and, in places, not even covering the rock.

Deposition Greatest in Valleys. — In the valleys, however, deposit has been greater and more varied, and there one finds moraines, kames, eskers, and other glacial and fluvio-glacial deposits. But even here deposit has produced only local and minor features, often quite out of scale with the major features of the glacial topography. In America deposition has produced its greatest effect on gently-un-

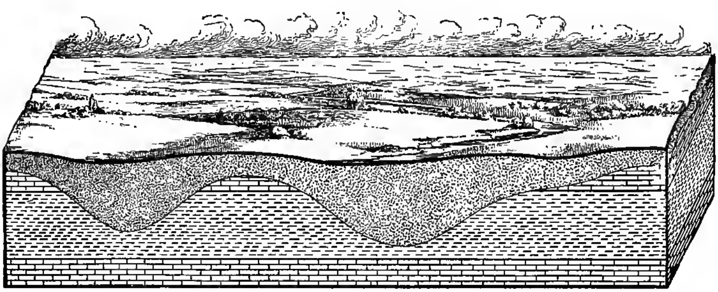


FIG. 209. — Drift deposits completely mantling the preglacial topography.

dulating surfaces near the ice border, as on the plains of the states in the Middle West. There, in places, the entire topography is drift-made (Fig. 209). The drainage features, as already noted, were profoundly modified and altered by the glacial invasion, and this is one of the most notable effects of the presence of the ice sheet.

INFLUENCE ON MAN

Glacial Soil. — In a multitude of ways the changes wrought by the ice sheet have had an influence on the occupants of the glacial region. The soil conditions have been completely changed, for the soil that previously existed as a result of rock decay has been swept off and replaced by glacial drift. In some sections bare rock slopes have been left, but generally a glacial deposit, of greater or less thickness, mantles the rock. This drift varies greatly and often within a very narrow area, being now clay, now sand or gravel, here stony, there free from stones. It is probable that the average quality of the soil has been improved; though locally, as in the low, hilly, eastern and southern part of New England, where the soil is often strewn with boulders brought from the higher land of the interior, the reverse is doubtless the case.

On this glacial soil plants encroached rapidly after the Glacial Period, so that its flora is now as abundant and varied as in the never-glaciated southern states. It is likewise fully as productive of plants used by man as before glaciation.

The animals that lived in the glaciated parts of North America and Europe before the ice age have likewise found the vegetation supported by the glacial soil to be suited to their demands and returned to all parts of the glaciated area. The mammoth and mastodon, however, have become extinct, though the presence of their skeletons in glacial deposits show they were here before the ice age. It is not certain that they were exterminated as a result of glaciation.

Sand, Gravel, and Clay as Economic Resources. — The glacial drift includes some material of local economic value, such as sand for building purposes, gravel useful in roads and cement, and clay extensively used in the manufacture of brick, tiles, flower pots and other coarse earthenware.

Water Supply. — Glacial drift is also of great value as a storage place for underground water. It undoubtedly has greater average depth than the preglacial deposits, and much of it is more porous, so that it has greater storage capacity. This is of importance for local water supply, and it is a factor of significance in maintaining the flow of streams in the glaciated country. The storage of underground water contributes toward the same end as the storage of water in lakes, and this regulation of river flow is a matter of much importance in streams that are navigable, or whose water is utilized for power.

Lakes, Falls, and Water Power. — The many lakes to which the glacier has given rise are useful in a number of other ways, as is shown in the next chapter. The influence of waterfalls has already been considered. Suffice it to repeat here that the abundant water power of glaciated regions has been a factor of profound significance in the industrial development of many regions, such as Wisconsin, New England, and many other regions. The Merrimac River of New Hampshire and Massachusetts, for example, has falls produced by glaciation at the manufacturing cities of Manchester, Lowell, and Lawrence. Had it not been for the glacial invasion, a large proportion of the waterfalls of the world would not exist.

Other Influences. — In a multitude of other ways the course of human affairs has been influenced by the ice invasion. Highways of travel have been modified by glacial erosion and deposition, determining the course of roads, canals, and railways on the land; and interior water routes have been made or modified. The sites of towns and cities have been determined, the levelness or ruggedness of farm land has been shaped, and local scenery, often of considerable economic value, has been evolved directly or indirectly by glacial

Fig. 210. — The continental glacier in United States. Showing area covered by the latest or Wisconsin glaciation, in white; the location of the Driftless Area in Wisconsin, Illinois, Iowa, and Minnesota; the area of older drift in Illinois, Iowa, Kansas, Nebraska, etc., in dark tint. (Howell and Chamberlin.)

action. Yosemite and Niagara Falls illustrate the latter influence, as do also many lakes to which man resorts.

Best Portions of United States, Great Britain, and Germany Glaciated. — It is a noteworthy fact that several of the greatest agricultural nations of the world, and the three leading manufacturing nations, which are also the most advanced industrially, are located partly in the belt of former glaciation. It would be absurd to claim that this is entirely the result of glaciation, for other factors are plainly to be seen; but it is nevertheless true that the effects of glaciation are to be reckoned as of fundamental importance.

Influence on History and Development of United States. — That this is true in the case of the United States is easy to see when one remembers that manufacturing in New England developed first as a response to the water power, which is still utilized; that water power, similarly caused by glacial action, is extensively used at various points as far west as Minneapolis; that the Great Lakes waterway is a product of glacial action; that the route of the Erie Canal was made possible by glacial lake deposit, and by glacial lake outflow into the Mohawk; that the level surface of the Central States, and the treelessness of the prairies which induced early and rapid settlement and development of agriculture, are due to glacial deposition; and that there are a multitude of minor influences of the glacial invasion. Surely, had there been no recent glaciation, the industrial history of the United States would have been notably different, and it is very doubtful if its development would have been anywhere near so rapid as it has been, or if its history would have been even approximately what it has been. Who can tell what the history of the French settlement of America would have been but for the influence of the Great Lakes? Or of the Central States, but for the ease of entering and settling them from the east? Or of the settlement of the Western States, but for the fact that people had so easily pushed their way westward across the Mississippi valley plains before the time of the discovery of gold in California? Yet each of these events in our history was influenced profoundly by conditions which the glacial invasion introduced.

Complexity of the Glacial Period

Advances and Recessions. — For the sake of clearness in the preceding discussion the subject has been treated as if there had been but a single period of glaciation. As a matter of fact, the ice invasion has been far more complex. There have been advances and recessions, as well as minor oscillations of the ice front, and there have been periods when the continental glaciers have either entirely disappeared or have receded far back toward the centres of dispersion. As yet there is not unanimity of opinion as regards the detailed history of this complexity, though there is general agreement that there was a complex series of advances and recessions, during each of which the ice margin phenomena were repeated, though partially or completely erased by each advance (Fig. 210).

Evidences of Complexity. — The evidences of advance and recession of the ice front are of several kinds, among which are the following: (1) There is more than one till sheet in many places, one overlying the other. (2) The till sheets vary in character, and the lower, or older, is often much weathered, as if long exposed to weathering before the overlying drift was laid down upon it. (3) The older till sheets extended farther south in the Mississippi valley than the drift of the last glacial advance, and they are not only more weathered, but have drainage of a much more mature pattern than that of the last drift. (4) There are buried gorges beneath the upper till, which were excavated in the interval between the ice advances, and since they are larger than the postglacial gorges, the interval between advances is believed to have been longer than postglacial time. (5) The till sheets of the different advances are often separated by soil beds, and peat deposits containing plant remains, showing that plants grew in the interval between advances. As far north as Toronto, the interglacial beds contain remains of plants that do not now live so far north.

The Glacial and Interglacial Stages. — Most glacialists are now convinced that there were two or more ice advances, separated by long intervals, or *interglacial* stages. It is thought by some observers that the older drift is 25 times as old as that of the latest glaciation. A full discussion of this subject does not fall within the province of physical geography, and it may be left here with the statement that, both in Europe and America, there is evidence which convinces many students of the subject that there were 4 or 5 stages of advance and recession, and some are not convinced of more than two notable advances, with one interglacial stage. The following table gives the names usually applied in the United States to the several glacial and interglacial stages, the Wisconsin being the latest. There is not yet complete agreement about the relationships of the Iowan, Illinoian, Peorian, and Sangamon.

Glacial	Interglacial
Wisconsin	
	Sangamon, Peorian
Iowan, Illinoian	
	Yarmouth
Kansan	
	Aftonian
Nebraskan, or pre-Kansan or Jerseyan	

Former Glacial Periods

The Glacial Period whose effects have been discussed in this chapter is not the only one of which there is record. In South Africa, for example, there is an extensive bed of till, consolidated to a hard rock, called tillite. It contains scratched stones, rests on glacially grooved bed-rock (Fig. 211), and bears evidence of being a deposit of a continental glacier. Yet it occurs in the tropical zone, and the ice movement was from the equatorial regions! This glacial period occurred far

Fig. 211. — Roche moutonnée made by the Permian ice sheet in South Africa. (R. B. Young.)

back in geological time, during the period of the earth's history known as the Permian; during the same period there was similar glaciation in India, Australia, and Brazil (Fig. 212). Evidence of still earlier glaciations is reported from Canada, from northern Norway, from China, and from Australia. It seems, therefore, that glaciation has been one of the phenomena of the geological past in regions far outside the range of possible glacial advance under present climatic conditions.

Hypotheses to Account for Former Glaciation

The Problem a Difficult One. — While the fact of the advance and retreat of the continental glaciers of the Glacial Period, and of earlier times, is firmly established, and most of the glacial phenomena are explained, science has so far failed in the establishment of any satisfactory explanation of the cause of the glaciation. It is not known either why the ice invasion came, or how long it lasted, or why, or exactly when, it disappeared. That it lasted for a long time, and had

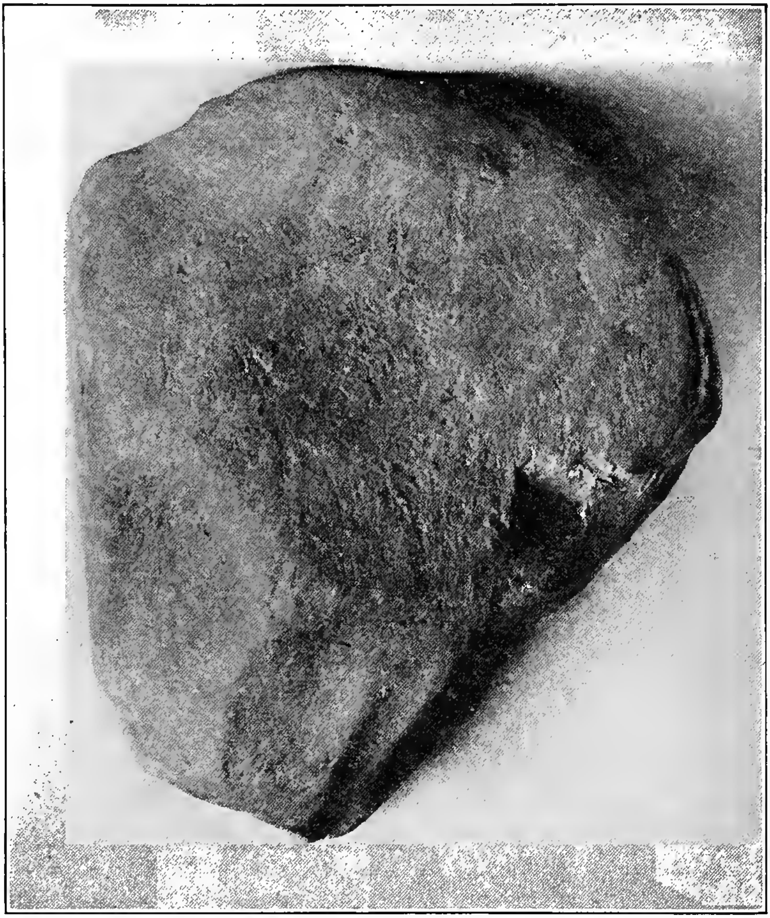


FIG. 212. — Glacial boulder from the Permian tillite of Brazil. (Woodworth.)

a complex history of advance and recession, is absolutely proved; and it is also clear that the recession was exceedingly recent, as geological time goes. Some estimates place the vanishing of the ice from the United States at from 5000 to 10,000 years ago, while others place the recession four or five times as far back in the past. None of the estimates are based upon sufficiently accurate data to warrant their acceptance. The best that can be said is that the recession of the ice was a recent event; indeed, there is reason for believing that it is still in progress, for ice sheets in Greenland and the Antarctic, and mountain valley glaciers, show evidence of fairly continuous shrinking.

While science has so far failed to demonstrate the cause for the continental glaciation, scientific men have been active in proposing hypotheses for consideration. In view of the fact that none of these is generally accepted, it does not seem worth while here to enter into a thorough consideration of them; but a brief statement of some of the hypotheses that have been put forward will serve to show the wide range of possibility.

Hypothesis of Geographical Changes. — It has been proposed that geographical changes are sufficient explanation, such as change in ocean currents, or change in the relative distribution of land and water, or change in the elevation of the land. These do not seem adequate explanations for the development of vast ice sheets, even though it be recognized that increase in snowfall, rather than excessive cold, is the important factor in the generation of an ice sheet. With the discovery of ice sheets of former ages within the tropics, these geographical explanations seem even less probable.

Hypothesis of Decreased Carbon Dioxide. — Another hypothesis is that the content of carbon dioxide and water in the atmosphere has varied in some stages, much of the former being given to the air by the exposure of sea beds and the disintegration of the limey animal remains, while at other times the carbon dioxide has been largely withdrawn in the processes of oxidation. Carbon dioxide interferes with radiation, and, therefore, an abundance of it tends to keep the earth's surface warm. When the carbon dioxide content is slight, radiation proceeds more rapidly and the land is colder. According to this explanation, glacial periods come when the carbon dioxide and water content of the air is sufficiently reduced in amount. Whether this theory would account for the development of glaciation within the tropical zone is doubtful, even with the assumption of elevation or other geographical changes.

Croll's Hypothesis. — The earth in its journey around the sun follows an elliptical path with the sun at one of the foci. In one part of the course, perihelion, the earth is nearer the sun than at the other, aphelion. The ellipticity of the orbit undergoes a slow variation, as that in the course of long periods of time the orbit becomes more elliptical or, in the opposite direction, more circular. This is called the eccentricity of the earth's orbit. When most eccentric the distance between the sun and earth is over 14,000,000 miles greater in aphelion than in perihelion, and the season is longer.

The earth's axis is inclined to the plane of the ecliptic so that we have winter and summer during every revolution. If the winter comes during aphelion, the sun is nearer and the season shorter than if it comes during perihelion. As a matter of fact, there is a constant change owing to the motion of the earth's axis, known as *precession of the equinoxes*. By this motion the axis swings so that each pole passes through a complete circle during a period of 21,000 years. Thus at intervals of 10,500 years the winter occurs alternately in aphelion and perihelion.

Croll's hypothesis was built upon these astronomical facts as a basis, the underlying idea being that during a period of great eccentricity, glaciation would alternately develop in each hemisphere as the precession of the equinoxes brought winter in the perihelion stage; while interglacial conditions would develop during the intermediate periods. This hypothesis was brilliantly presented, much discussed, and found many adherents, but, even though numerous geographical conditions were invoked as accessory to the main theory, it has been quite generally considered as an inadequate hypothesis and now finds few supporters.

Other Astronomical Hypotheses. — Much more vague astronomical hypotheses have been proposed, such as the hypothesis that the sun is a variable star, and others much less probable. Naturally such hypotheses cannot be tested, for we have not the data upon which to investigate them. It is surely possible that the heat emitted from the sun varies from time to time, and that it may be sufficiently variable to account for the development of ice sheets; but as yet there are no facts which can be considered as proof of this.

Hypothesis of a Shifted Axis of the Earth. — Finally, the hypothesis has been proposed that the axis of rotation of the earth changes position under the effect of influences as yet unknown, and that the position of the poles themselves is, therefore, changed. If the pole were shifted to South Africa, an ice sheet would naturally develop; and so would ice sheets develop on the two sides of the North Atlantic if the pole were shifted to a point between northern Europe and America. This hypothesis meets with the serious objection that there is no known cause for such a change, and, therefore, that it is improbable. Furthermore, it fails to explain the widespread distribution of areas where mountain valley glaciers were more extensive than now, some of them farther away from the position inferred for the changed pole than they are from the present pole.

Explanation of Glacial Periods Unsettled. — From this multitude of hypotheses it has not yet seemed possible to select one that has a sufficient body of fact in support of it to lead to its general adoption. Therefore the cause of the Glacial Period must be reckoned as one of the unsolved problems of science, the existence of which is one of the great incentives to scientific research. With the success that has in the past attended the patient investigation of the problems of nature, we may look forward hopefully to a time when this phenomenon will also pass into the realm of the known.

References to Literature

Louis Agassiz. Geological Essays, 2d series, Boston, 1876, 229 pp.
W. C. Alden. The Drumlins of Southeastern Wisconsin, Bull. 272, U. S. Geol. Survey, 1905, 46 pp.; The Delavan Lobe of the Lake Michigan Glacier, Prof. Paper 34, U. S. Geol. Survey, 1905, 106 pp.; Criteria for Discrimination of the Age of Glacial Drift Sheets, Journ. Geol., Vol. 17, 1909, pp. 624–709.
S. H. Ball and M. K. Shaler. A Central African Glacier of Triassic Age, Journ. Geol., Vol. 18, 1910, pp. 681–701.
A. von Bohmersheim. Geschichte der Moränenkunde, Abhandlungen der K. K. Geogr. Gesell. Wien, Vol. 3, 1901, 334 pp.
T. G. Bonney. Some Aspects of the Glacial History of Western Europe, Scottish Geog. Mag., Vol. 26, 1910, pp. 505–532.
J. C. Branner. The Supposed Glaciation of Brazil, Journ. Geol., Vol. 1, 1893, pp. 753–772.
A. P. Brigham. Topography and Glacial Deposits of Mohawk Valley, Bull. Geol. Soc. Amer., Vol. 9, 1898, pp. 183–210.
C. Calvin. Present Phase of the Pleistocene Problem of Iowa, Bull. Geol. Soc. Amer., Vol. 20, 1909, pp. 133–152.
T. C. Chamberlin. Terminal Moraine of the Second Glacial Epoch, 3d Ann. Rept., U. S. Geol. Survey, 1883, pp. 291–402; Rock Scorings of the Great Ice Invasions, *ibid.*, 7th Ann. Rept., 1888, pp. 147–248; Genetic Classification of the Drift, Journ. Geol., Vol. 2, 1894, pp. 517–538; The Classification of American Glacial Deposits, *ibid.*, Vol. 3, 1895, pp. 270–277; An Attempt to Frame a Working Hypothesis of the Cause of Glacial Periods on an Atmospheric Basis, *ibid.*, Vol. 7, 1899, pp. 544–584, 667–685, 751–787.
T. C. Chamberlin and R. D. Salisbury. The Driftless Area of the Upper Mississippi Valley, 6th Ann. Rept., U. S. Geol. Survey, 1885, pp. 199–322; Earth History, Vol. 3, 1906, pp. 327–446.
A. P. Coleman. Glacial and Inter-Glacial Deposits near Toronto, Journ. Geol., Vol. 3, 1895, pp. 622–645; *ibid.*, Vol. 9, 1901, pp. 285–310; The Lower Huronian Ice Age, *ibid.*, Vol. 16, 1908, pp. 149–158.
J. Croll. Climate and Cosmology, New York, 1886; Climate and Time, New York, 1890.
W. O. Crosby. Origin of Eskers, Amer. Geol., Vol. 30, 1902, pp. 1–39.
Charles Darwin. Observations on the Parallel Roads of Glen Roy, Phil. Trans. Roy. Soc., Vol. 8, 1839, pp. 39–82.
T. W. E. David. Conditions of Climate at Different Geological Epochs, Compte Rendu, 10th International Geological Congress, 1907, pp. 437–482.
W. M. Davis. Structure and Origin of Glacial Sand Plains, Bull. Geol. Soc. Amer., Vol. 1, 1890, pp. 195–202; Observations in South Africa, Bull. Geol. Soc. Amer., Vol. 17, 1906, pp. 377–450.
G. M. Dawson and R. G. McConnell. Glacial Deposits of Southwestern Alberta, Bull. Geol. Soc. Amer., Vol. 7, 1896, pp. 31–66.
J. W. Dawson. The Canadian Ice Age, Montreal, 1893, 301 pp.
H. L. Fairchild. Glacial Waters in Lake Erie Basin, Central New York, and Black and Mohawk Valleys, N. Y., Bulls. 106 (1907), 127 (1909), and 160 (1912), N.Y. State Museum; Drumlins of Central Western New York, *ibid.*, Bull. 111 (1907); Ice Erosion Theory a Fallacy, Bull. Geol. Soc. Amer., Vol. 16, 1905, pp. 13–74.
A. Falsan. La Période Glaciaire, Paris, 1889, 364 pp.
M. L. Fuller. Geology of Long Island, Prof. Paper 82, U. S. Geol. Survey, 1914, 231 pp.
G. de Geer. Quaternary Sea Bottoms of Western Sweden, Guidebook 23, International Geological Congress, 1910, 57 pp.
J. Geikie. The Great Ice Age, New York, 1894; Classification of European

Glacial Deposits, Journ. Geol., Vol. 3, 1895, pp. 241–269; *ibid.*, Vol. 5, 1897, pp. 113–125.

G. K. Gilbert. Old Tracks of Erian Drainage in Western New York, Bull. Geol. Soc. Amer., Vol. 8, 1897, pp. 285–286; Modification of the Great Lakes by Earth Movement, Nat. Geog. Mag., Vol. 8, 1897, pp. 233–247; 18th Ann. Rept., U. S. Geol. Survey, Part 2, 1898, pp. 601–647; Crescentic Gouges on Glaciated Surfaces, Bull. Geol. Soc. Amer., Vol. 17, 1906, pp. 303–316.

J. W. Goldthwait. A Reconstruction of Water Planes of the Extinct Glacial Lakes in the Lake Michigan Basin, Journ. Geol., Vol. 16, 1908, pp. 459–476; Glacial Cirques near Mt. Washington, Amer. Journ. Sci., 4th series, Vol. 35, 1913, pp. 1–19; Shorelines of the Extinct Lakes Algonquin and Nipissing in Southwestern Ontario, Memoir 10, Canadian Geol. Survey, 1910, 57 pp.

A. M. Hansen. The Glacial Succession in Norway, Journ. Geol., Vol. 2, 1894, pp. 123–144.

C. H. Hitchcock. Glaciation of the Green Mountain Range, Vermont Geol. Survey, Vol. 4, 1904, pp. 67–85.

W. H. Hobbs. The Diamond Field of the Great Lakes, Journ. Geol., Vol. 7, 1899, pp. 375–388; The Pleistocene Glaciation of North America Viewed in the Light of our Knowledge of Existing Continental Glaciers, Bull. Amer. Geog. Soc., Vol. 43, 1911, pp. 641–659.

W. Howchin. Australian Glaciations, Journ. Geol., Vol. 20, 1912, pp. 193–227.

G. D. Hubbard. A Case of Geographic Influence upon Human Affairs, Bull. Amer. Geog. Soc., Vol. 36, 1904, pp. 145–157.

E. Huntington. Some Characteristics of the Glacial Period in Non-Glaciated Regions, Bull. Geol. Soc. Amer., Vol. 18, 1907, pp. 351–388.

T. T. Jamieson. On the Parallel Roads of Glen Roy, Quart. Journ. Geol. Soc., Vol. 19, 1863, pp. 235–259.

G. H. Kinahan and H. M. Close. General Glaciation of Iar-Connaught and its Neighborhood in the Counties of Galway and Mayo, Dublin, 1872.

G. W. Lamplugh. On British Drifts and the Interglacial Problem, Nature, Vol. 74, 1906, pp. 387–400; Proc. Yorkshire Geol. Soc., Vol. 17, 1911, 27 pp.

Frank Leverett. Illinois Glacial Lobe, Monograph 38, U. S. Geol. Survey, 1899, 817 pp.; Erie and Ohio Basins, Monograph 41, 1902, 802 pp.; Geol. Survey of Michigan, Publications 7 and 9, 1912; Weathering and Erosion as Time Measures, Amer. Journ. Sci., Vol. 177, 1909, pp. 349–368; Comparison of North American and European Glacial Deposits, Zeitschrift für Gletscherkunde, Vol. 4, 1910, pp. 241–295, 321–342.

H. C. Lewis. Report on the Terminal Moraine in Pennsylvania and Western New York, Second Geol. Survey, Pennsylvania, Rept. Z, 1884, 299 pp.

W J McGee. Pleistocene History of Northeastern Iowa, 11th Ann. Rept., U. S. Geol. Survey, 1891, pp. 189–577.

Lawrence Martin. The Pleistocene of the Lake Superior Region, Monograph 52, U. S. Geol. Survey, 1911, pp. 427–459.

J. S. Newberry. Notes on the Surface Geology of the Basin of the Great Lakes, Proc. Bost. Soc. Nat. Hist., Vol. 9, 1865, pp. 42–46; On the Origin and Drainage of the Basins of the Great Lakes, Proc. Amer. Phil. Soc., Vol. 20, 1883, pp. 91–95; The Eroding Power of Ice, School of Mines Quarterly, Vol. 6, 1885, pp. 142–153.

A. Penck. Climatic Features of the Pleistocene Ice Age, Geog. Journ., Vol. 27, 1906, pp. 182–187.

A. C. Ramsay. On the Glacial Origin of Certain Lakes in Switzerland and Elsewhere, Quart. Journ. Geol. Soc., Vol. 18, 1862, pp. 185–204; Amer. Journ. Sci., 2d series, Vol. 35, 1863, pp. 324–345.

J. L. Rich. Local Glaciation in the Catskill Mountains, Journ. Geol., Vol. 14, 1906, pp. 113–121; Marginal Glacial Drainage Features in the Finger Lake Region, *ibid.*, Vol. 16, 1908, pp. 527–548.

I. C. Russell. A Geological Reconnaissance in Central Washington, Bull. 108, U. S. Geol. Survey, 1893, pp. 87–96; A Geological Reconnaissance along the North Shore of Lakes Huron and Michigan, Geol. Survey Michigan, Report for 1904, pp. 33–150; *ibid.*, Report for 1906, 91 pp.; I. C. Russell and Frank Leverett, Folio 155, U. S. Geol. Survey, 1908.

I. C. Russell and Others. For maps showing former extent of mountain glaciation in America, see the following U. S. Geol. Survey and other maps: **Russell**, Pl. 29, 8th Ann. Rept., and Pl. 18 in Part 2, 20th Ann. Rept.; **Weed**, Pl. 1, Bull. 104; **Lindgren**, Folios 39, 31; **Lawson**, Pl. 31, p. 306, Vol. 3, Univ. Cal. Publications; **Willis**, Pl. 8, Prof. Paper 19; **Tarr and Martin**, Map 1, Alaskan Glacier Studies; **Calhoun**, Pl. 1, Prof. Paper 50; **Bastin and Blackwelder**, Folios 141, 142, and Pl. 28 in Prof. Paper 51; **Atwood**, Pls. 4, 10, Prof. Paper 61, and Figs. 1–4, pp. 390–398, Vol. 20, Journ. Geol.; **Capps**, Pl. 1, Bull. 386; **Ball**, Pls. 4, 5, Prof. Paper 63; **Cross and Howe**, Folio 153; **Ransome**, Pl. 1, Prof. Paper 75; **Hole**, Pl. 1, p. 502, Vol. 20, Journ. Geol.; **Alden**, Pl. 13, Vol. 24, Bull. Geol. Soc. Amer.

R. D. Salisbury. The Glacial Geology of New Jersey, N. J. Geol. Survey, Vol. 5, 1902, 802 pp.; Articles on the Drift, Journ. Geol., Vol. 1, 1893, pp. 61–84; Vol. 2, 1894, pp. 613–632, 708–724, 837–851; Vol. 3, 1895, pp. 70–97; Vol. 4, 1896, pp. 948–970; Vol. 8, 1900, pp. 426–432; Vol. 17, 1909, pp. 589–599; Glacial Work in the Western Mountains in 1901, *ibid.*, Vol. 9, 1901, pp. 718–731; Prof. Paper 51, U. S. Geol. Survey, 1906, pp. 71–91.

R. D. Salisbury and W. W. Atwood. Geography of the Region about Devils Lake and the Dalles of the Wisconsin, Bull. 5, Wis. Geol. Survey, 1900, 151 pp.

E. H. L. Schwarz. The Three Paleozoic Ice Ages of South Africa, Journ. Geol., Vol. 14, 1906, pp. 683–691.

N. S. Shaler. Description of glacial features in U. S. Geol. Survey publications: Marthas Vineyard, 7th Ann. Rept., 1888, pp. 297–363; Nantucket, Bull. 53, 1889, pp. 601–653; Cape Cod, 18th Ann. Rept., Part 2, 1898, pp. 503–593; Narragansett Basin, Monograph 33, 1899, pp. 64–76.

B. Shimek. The Loess and the Lansing Man, Amer. Geol., Vol. 32, 1903, pp. 353–369.

G. H. Stone. The Glacial Gravels of Maine, Monograph 34, U. S. Geol. Survey, 1899, 499 pp.

A. Strahan. Glacial Phenomena of Paleozoic Age, Quart. Journ. Geol. Soc., Vol. 53, 1897, pp. 137–146.

R. S. Tarr. The Central Massachusetts Moraine, Amer. Journ. Sci., 3d series, Vol. 43, 1892, pp. 141–145; Glaciation of Mount Ktaadn, Maine, Bull. Geol. Soc. Amer., Vol. 11, 1900, pp. 433–448; Evidence of Glaciation in Labrador and Baffin Land, Amer. Geol., Vol. 19, 1897, pp. 191–197; The Origin of Drumlins, Amer. Geol., Vol. 13, 1894, pp. 393–407; Physical Geography of New York State, New York, 1902, Chapters IV, VII, VIII, IX, and XII; Glacial Erosion in the Scottish Highlands, Scottish Geog. Mag., Vol. 24, 1908, pp. 575–587; Papers on the Finger Lake Region of Central New York, — Bull. Geol. Soc. Amer., Vol. 5, 1894, pp. 339–356; Bull. Amer. Geog. Soc., Vol. 37, 1905, pp. 193–212; Amer. Geol., Vol. 33, 1904, pp. 271–291; Journ. Geol., Vol. 14, 1906, pp. 18–21; *ibid.*, Vol. 12, 1904, pp. 69–82; Bull. Geol. Soc. Amer., Vol. 16, 1905, pp. 215–228; Watkins-Catatonk Folio, U. S. Geol. Survey, No. 169, 1909.

F. B. Taylor. Glacial and Postglacial Lakes of the Great Lakes Region, Smithsonian Rept. for 1912, No. 2201, pp. 291–327; The Moraine Systems of Southwestern Ontario, Trans. Canadian Institute, Vol. 10, 1912, pp. 1–23; Correlation and Reconstruction of Recessional Ice Borders in Berkshire County, Massachusetts, Journ. Geol., Vol. 11, 1903, pp. 323–364; The Richmond and Great Barrington Bowlder Trains, Bull. Geol. Soc. Amer., Vol. 21, 1910, pp. 747–752.

W. G. Tight. Drainage Modifications in Southeastern Ohio, Prof. Paper 13, U. S. Geol. Survey, 1903, 111 pp.

J. E. Todd. The Moraines of the Missouri Coteau, Bull. 144, U. S. Geol. Survey, 1896, 71 pp.; The Moraines of Southeastern South Dakota, *ibid.*, Bull. 158, 1899, 171 pp.

C. F. Tolman, Jr. The Carbon Dioxide of the Oceans and its Relations to the Carbon Dioxide of the Atmosphere, Journ. Geol., Vol. 7, 1899, pp. 585–618.

J. B. Tyrrell. The Glaciation of North Central Canada, Journ. Geol., Vol. 6, 1898, pp. 147–160.

Warren Upham. Glacial Lake Agassiz, Monograph 25, U. S. Geol. Survey, 1896, 658 pp.; On the Cause of the Glacial Period, Amer. Geol., Vol. 6, 1890, pp. 327–339.

Warren Upham, Frank Leverett, N. S. Shaler, and W. O. Crosby. Climatic Conditions of the Glacial Period, Proc. Bost. Soc. Nat. Hist., Vol. 24, 1889, pp. 450–467.

U. S. Geological Survey Folios. The following folios of the Geologic Atlas of United States are among the best of those which have special maps and texts dealing with the glacial features.

Rockland, Me.	Niagara, N.Y.	Aberdeen-Redfield, S.D.
Holyoke, Mass.	Ann Arbor, Mich.	Jamestown-Tower, N.D.
New York City, N.Y.	Chicago, Ill.	Cloud Peak-Fort McKinney, Wyo.
Passaic, N.J.	Milwaukee, Wis.	
Watkins-Catatonk, N.Y.	Tallula-Springfield, Ill.	Tacoma, Wash.

A. C. Veatch. Diversity of the Glacial Period in Long Island, Journ. Geol., Vol. 11, 1903, pp. 762–776.

F. Wahnschaffe. Die Oberflächengestaltung des Nord Deutschen Flachlandes, Forschungen zu D. Landes und Volkskunde, Vol. 6, 1891, 166 pp.; *ibid.*, 3d edition, 1909.

David White. Carboniferous Glaciation in the Southern and Eastern Hemispheres, Journ. Geol., Vol. 3, 1889, pp. 299–330; *ibid.*, Vol. 15, 1907, pp. 615–633.

B. Willis. Changes in River Courses in Washington Territory due to Glaciation, Bull. 40, U. S. Geol. Survey, 1887, 10 pp.; Drift Phenomena of Puget Sound, Bull. Geol. Soc. Amer., Vol. 9, 1898, pp. 111–162; Research in China, Publication 54, Carnegie Institution, 1907, pp. 267–269.

J. H. Wilson. The Glacial History of Nantucket and Cape Cod, Columbia Univ. Press, Geol. Series, Vol. 1, 1906, 90 pp.

J. B. Woodworth. An Attempt to Estimate the Thickness of the Ice Blocks which gave rise to Lakelets and Kettle Holes, Amer. Geol., Vol. 12, 1893, pp. 279–284; Nantucket, A Morainal Island, Journ. Geol., Vol. 7, 1899, pp. 226–236; Ancient Water Levels of the Champlain and Hudson Valleys, Bull. 84, N. Y. State Museum, 1904, pp. 65–265; Pleistocene Geology of the Mooers Quadrangle, *ibid.*, Bull. 83, 1905, 60 pp.; Permian Glacial Deposits of South Brazil, Bull. Mus. Comp. Zoöl., Vol. 56, 1912, pp. 52–91.

G. F. Wright. Ice Age in North America, New York, 1889, 1911; Man and the Glacial Period, New York, 1892; The Glacial Boundary in Western Pennsylvania, Ohio, etc., Bull. 58, U. S. Geol. Survey, 1890, 112 pp.

TOPOGRAPHIC MAPS

Driftless Area

Cross Plains, Wis.	Lancaster, Wis.	Sparta, Wis.

Drumlins and Ground Moraine

Hartford, Conn.	Boston Bay, Mass.	Weedsport, N.Y.
Oswego, N.Y.	Watertown, Wis.	Waterloo, Wis.
Auburn, N.Y.	Sun Prairie, Wis.	Fond du Lac, Wis.

Glacial Lake Overflow Channels

Baldwinsville, N.Y.	Lacon, Ill.	Ottawa, Ill.

Moraines

Northville, S.D.	Marthas Vineyard, Mass.	Whitewater, Wis.
St. Croix Dalles, Wis.	Tower, N.D.	Ann Arbor, Mich.
Eagle, Wis.	Edgeley, N.D.	Gloversville, N.Y.
St. Paul, Minn.	Minnetonka, Minn.	Easthampton, N.Y.

Outwash Plains

Elmira, N.Y.	Huron, S.D.	Brooklyn, N.Y.
Janesville, Wis.	Mt. Sterling, Ohio	Wyndmere, N.D.

CHAPTER X

LAKES AND SWAMPS

Characteristics of Lakes

General Features. — A lake is a body of standing water on the land. Lakes occur, therefore, where there is an obstruction to the free run-off of surface water. If the obstruction be slight, as on level ground, a swamp may result; but if it be sufficient to give rise to a depression, standing water may accumulate. There is every gradation from swamp to lake; and among lakes, there is every gradation from very shallow to very deep bodies of water. There is also great variation in size. Some are so small that they are called ponds, others are so large that they are often called inland seas. From the standpoint of physiography there is no distinction to be drawn between lakes and ponds; and even in popular usage, there is no definite distinction excepting that ponds are small lakes; but sometimes fair-sized lakes are called ponds, and much smaller bodies of water are called lakes.

The Variety of Lakes. — The accompanying table gives the area, altitude, and depth of some of the best-known lakes of the world.

From it one sees that far the largest lake is Caspian Sea, while the largest fresh-water lake is Lake Superior. There is great range in altitude of the surface, for lakes may lie at any level up to the snow line, and their surface may even be below the sea level in arid interior basins. In depth there is also a great range, and the bottoms of many lakes lie below sea level. It is, perhaps, needless to say that the myth of "bottomless lakes" is wholly without foundation, and many such lakes are in reality quite shallow. Every lake is a reservoir in which a considerable volume of water is stored. It is estimated that the volume of water in the deep basin of Lake Superior is about 2800 cubic miles, while in the much shallower and smaller Lake Erie are about 130 cubic miles of water. The total volume of water in the five Great Lakes is about 5500 cubic miles. The water of these lakes comes from the rainfall, some of it entering by direct run-off, some from underground sources, as in the case of rivers. Because of the vast volume, large, deep lakes are not subject to very great fluctuations in level with variations in rainfall. They serve, therefore, as regulators of streams that issue from them.

Name of Lake	Area in Square Miles	Elevation in Feet	Greatest Depth in Feet
Aral Sea	26,900	160	225
Argentino	590	613	122 +
Athabasca	2,850	690	——
Baikal	12,500	1,312	4,997
Balkash	7,800	780	70
Bangweolo	1,670 [2]	3,760	——
Buenos Aires	780	745	——
Caspian Sea	169,000	−85 [1]	2,400
Cayuga	67	381	435
Chad	10,000 [2]	850	20
Chelan	85	1,079	1,500
Como	60	650	1,340
Crater	25	6,239	2,000
Dead Sea	370	−1310 [1]	1,330
Erie	9,990	573	210
Eyre	4,000 [2]	70	——
Garda	189	215	1,135
Great Bear	11,200	391	270 +
Great Salt	2,360	4,218	30–50
Great Slave	10,100	520	650 +
Huron	22,322	582	750
Iliamna	1,100	50	600 +
Ladoga	7,000	60	730
Manitoba	1,850	810	——
Michigan	21,729	582	870
Nicaragua	3,600	110	83
Nyassa	14,000	1,500	600 +
Ontario	7,104	247	738
Pontchartrain	600	5 [3]	16
Salton Sea	247	−253 [1]	34 [4]
Superior	30,829	602	1,008
Tanganyika	12,650	2,560	4,188
Titicaca	3,300	12,875	700
Van	1,400	5,214	——
Victoria	30,000	4,000	590 +
Winnipeg	9,400	710	70

[1] Below sea level. [2] Variable with the season. [3] Or less. [4] In 1906.

Variations in Lake Level. — The levels of lakes will, however, slowly rise and fall as the precipitation varies. This is especially noticeable in small lakes, as a direct result of run-off; in large lakes it is more noticeable as an effect of seasonal variations, a dry season being followed by a lowering of the lake level, a wet season by a rise. This is in large part a response to variations in the amount of underground water contributed. There are also variations in the levels of large lakes as a result of wind direction, for, when the wind blows steadily for a long enough time, water is drifted from one end of the lake to the other, causing a rise of the surface at the end to which the water drifts. This may be seen on Lake Cayuga in central New York.

Ordinarily lakes lie below the zone of permanent saturation or the water table, and their volume is being augmented by the movement of underground water toward them; but some lakes, especially small ones, lie above the permanent water table. Such lakes suffer leakage, and if the drainage area is small and the surrounding rock porous, such as gravel or sand, they may entirely disappear during periods of drought. Another cause for variation in lake level is evaporation, to which all lakes are subjected. In an arid climate evaporation may exceed supply, and then fluctuation of level follows. It is for this reason, together with seepage, that shallow Lake Chad fluctuates so in area, becoming greatly expanded during the seasons of rains, and shrinking during the dry season. In desert regions there are many basins with no water, or with water only for a part of the year.

Lakes without Outlets. — Lakes in which evaporation exceeds water supply will have their surfaces lowered, so that they cannot overflow the lowest point in the rim of the basin; that is, they have no outlet. In that case, they soon become transformed to salt lakes, like Aral Sea, Caspian Sea, Dead Sea, and Great Salt Lake. The reason for this is that the mineral substances which the surface and underground waters bring to the lake in solution cannot escape by evaporation. They, therefore, become more and more concentrated; and, since salt is one of the substances carried, in small quantities, in solution the lake water gradually grows saline. A lake with outlet suffers no such concentration of dissolved mineral matter; but we may be certain that if such a lake, say Lake Superior, were lowered by evaporation so that it no longer had outflow, and its water had no underground escape, as by seepage, it would become a salt lake. It would in time become even much salter than the sea itself, as the Dead Sea and Great Salt Lake are.

The Streams Related to Lakes. — Most lakes have *outlet* streams, though this is not true (*a*) of lakes in arid regions where evaporation exceeds supply, or (*b*) of lakes where seepage exceeds the supply. There are also *inlet* streams, usually at the heads of lakes; but such streams may also be absent in lakes of small size, or lakes of small drainage area. Some lakes of this sort receive practically their entire supply from the rainfall and slight contributions of run-off from their narrow rim. This is true, for instance, of even so large a body of fresh water as Crater Lake, Oregon, whose main supply is from direct rainfall and from an exceedingly limited drainage area, while it discharges, not through an outflow channel, but by seepage.

Besides rainfall, rain-born rills, underground supplies, and an inlet stream, most lakes receive water from tributaries. Large lakes, like one of the Great Lakes, receive water from hundreds of such tributary streams, each contributing sediment as well as water. Sometimes the mouths of the tributary streams are at the heads of bays, sometimes they project as delta points into the lake. There is, in fact, great variety in form of lake, some being long, narrow, and straight-walled, some circular, some notably irregular. The form of the lake varies with the origin, and with the topographic features of the region in which the lake basin is developed.

The outlet streams from lakes are well regulated as to volume. The St. Lawrence, flowing from the Great Lakes, has a fairly steady volume and no floods, while the Ohio, with no lakes, has floods which rise 50 to 60 feet. The St. Lawrence is clear, while the Missouri, without headwater lakes, is extremely muddy.

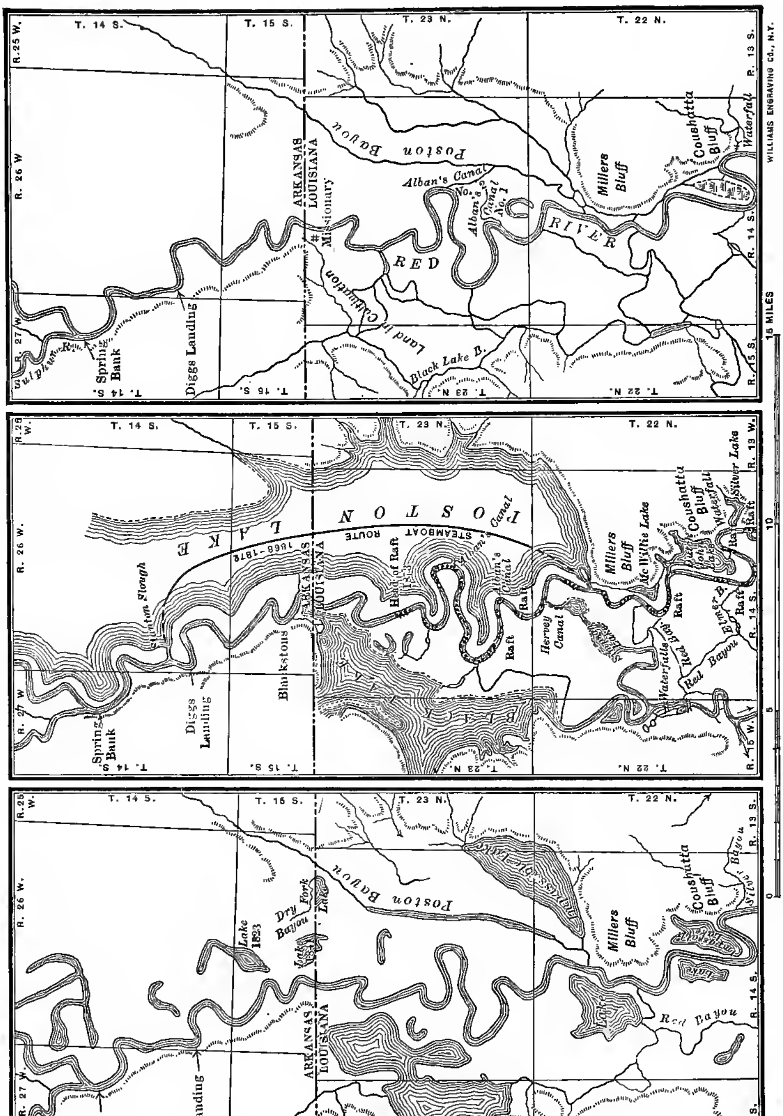
Causes for Lake Basins

Davis's Classification. — There have been numerous classifications of lakes, but the one that seems to possess the most philosophical basis is the one proposed by Davis. This considers them a phase of drainage, their basins being local depressions obstructing the free run-off of water. Lakes are episodes in the history of valley development by the action of running water, their basins serving as the storage places for some of this water, as the seat of deposit for river sediment, and as temporary baselevels for the inlet and tributary streams. Since the lakes are an integral part of the land drainage, and their basins are parts of the valleys of river systems, it seems proper to consider lakes and lake basins as phases of river valley development.

Upon this basis, lakes may be classified as (1) lakes consequent upon new land surfaces, (2) lakes formed in the course of the normal development of river valleys, and (3) lakes due to accidental interruptions to normal development.

Consequent Lakes. — Upon any new land surface, such as a sea bottom raised above sea level to form a coastal plain, there may be depressions, in which standing water will gather. Lakes thus formed are consequent upon original irregularities, and may, therefore, be classed as consequent lakes. Some of the shallow lakes of the southern part of Florida are of this origin. Any new land surface, such as a lava flow, or a sheet of till, or a moraine, may have irregularities in which consequent lakes form. Thousands of such lakes are dotted over the surface of the glaciated country, most of them so small as to be commonly called ponds. Consequent lakes also occur in depressions on the bottoms of extinct lakes such as Lake Agassiz. Even so large a lake as Winnipeg is at least partly of consequent origin.

Lakes of Normal Development. — As we have seen, lakes are developed upon floodplains during the normal meandering of rivers. Such lakes are narrow and shallow, usually with curved outline, and in their most typical form are ox-bow lakes. The upward growth of a floodplain may pond back the mouths of tributaries, making their lower courses broad, lake-like expanses, as in the case of the tributaries of the Amazon. Or low-grade streams may be ponded by the growth of vegetation, or by the accumulation of " rafts " of tree trunks (Fig. 213), as in the case of the tributaries to the Red River of



1837–38 1871–72 1902

FIG. 213. — Three stages in the making and destruction of raft lakes in the Red River of Louisiana and Arkansas. (Veatch.)

Louisiana. Or a tributary stream, depositing sediment in the main river may pond it back, forming lake-like expanses. This is illustrated in the Colorado River (Fig. 66), where there are lake-like stretches above the coarse deposits made by steep-grade tributaries. It is also illustrated in the Mississippi River above the mouth of the Chip-

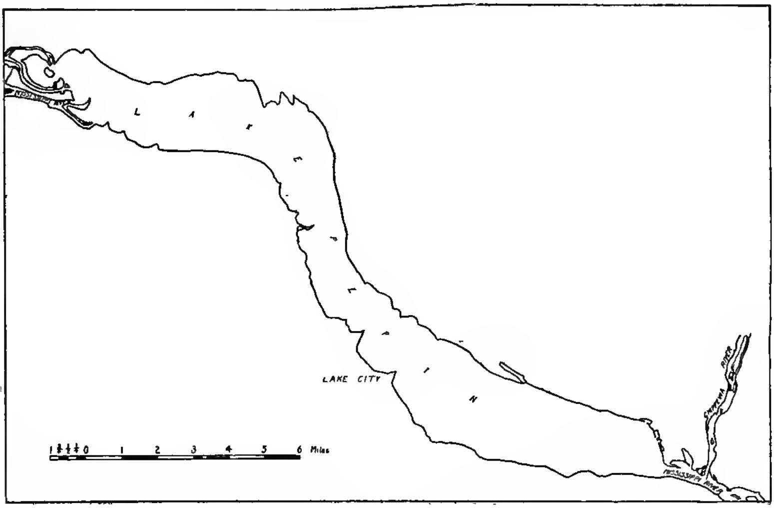


FIG. 214.—Lake Pepin, where a tributary dams back the main stream of the Mississippi.

pewa, where the river expands into what is called Lake Pepin (Fig. 214). Glaciers may also pond back a river, as the Copper River, Alaska (Fig. 377).

A river bed is really a succession of basins of small size, and, as such a stream dries up, a chain of tiny lakes succeeds the stage of running water. An abandoned stream course may give rise to more permanent lakes of this sort. Thus, south of Syracuse, N.Y., there is a small body of water called Jamesville Lake, in a pot hole excavated at the base of a waterfall which was probably as large as Niagara, in a marginal channel that flowed along the edge of the receding ice sheet. There are similar lakes near Coulee City, Washington, at the base of an abandoned waterfall of the Columbia River which was diverted southward during the Glacial Period and formed the Grand Coulee (Fig. 337), a dry stream course in whose bottom are many saline lakes. Small lakes in depressions on the beds of abandoned marginal channels are not uncommon in formerly glaciated regions.

Lakes develop at the mouths of rivers, both where they enter the sea through bays, and where they enter it over deltas. In the former case sand bars are often thrown up across the mouth of the bay, either partly or completely imponding the waters. Lakes and ponds of this

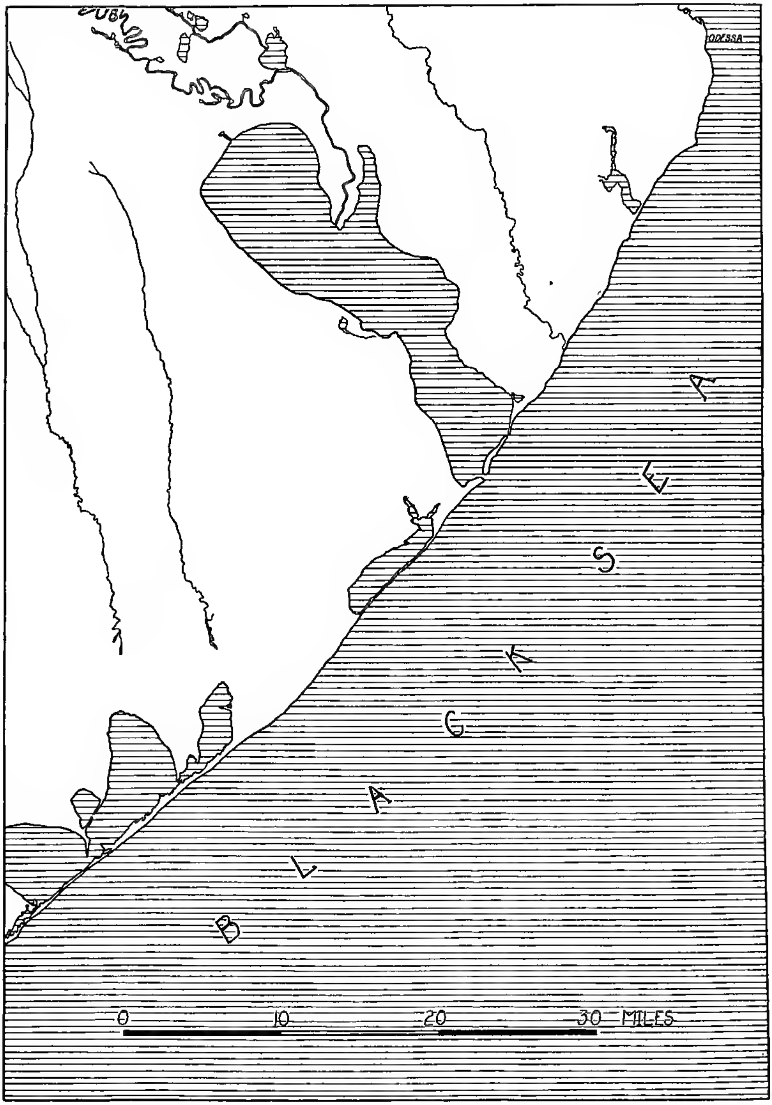


FIG. 215. — Coastal lakes in Russia near Odessa.

origin are common along the shores of the Great Lakes, and along the ocean, as on Martha's Vineyard, Mass., and along the Black Sea southwest of Odessa (Fig. 215). Delta lakes develop by the irregular growth of the delta, combined with the action of the waves. Thus the outward growth of the Mississippi delta has left an unfilled depression called Lake Pontchartrain (Fig. 90), and there are partly or completely formed lakes of similar origin on this and other deltas, such as the Danube (Fig. 92).

On the land the growth of alluvial fans may establish a dam across a stream and thus form a lake, as King River has done in the Valley of California, forming Tulare Lake.

In the course of the development of underground drainage the settling of the surface gives rise to depressions, or sink holes, which, though normally open at the bottom, are sometimes filled either naturally or by man, and they become the seat of sink hole ponds. Such lakes abound in limestone regions.

Lakes due to Accident. — There are a multitude of causes by which basins may be formed, usually by the development of a dam across a preëxisting drainage line. There are, for example, thousands of dams of organic origin. Man is now one of the most effective lake makers, placing dams across streams to impound water for his service for many uses, such as irrigation, water-power supply, and municipal drinking supply. Thousands of lakes and ponds have been made by man. In North America, before white men entered to destroy it, the beaver was a lake maker of great importance. In more remote regions, or in places where protected from the hunters, it still builds its dams of sticks, and lives in the quiet waters of the pond above. The growth of plants may so check the run-off as to cause shallow lakes, as in the case of Lake Drummond in Dismal Swamp.

Landslides and avalanches sometimes cause lakes by forming dams across streams, especially in lofty mountains, but on a smaller scale even in hilly regions. Sand carried by the wind is often deposited across streams, especially along the coast line, forming small ponds. Lava flows also dam some streams and form lakes, such as Snag Lake, California, the Sea of Tiberias in the Jordan valley, and numerous small lakes in the central plateau of France and other volcanic regions. In 1783 a lava flow in Iceland dammed back side streams, making lakes which covered villages and destroyed much life. The craters of volcanoes are basins and in these lakes often occur after the volcanic activity ceases. These are normally circular in outline, and are sometimes of great depth. Crater Lake in Oregon is an instance of such lakes, and there are others in the Auvergne region of central France, in the Eifel region of western Germany, in Italy, as at Lake Nemi near Rome, and Lake Avernus near Naples, and in many other places.

The level of the land is subject to change by uplift or by depression, and changes of this sort have been in progress during the geological past. During such changes basins may be formed by the down-warping of a portion of the surface, or by the uprising of a region. Basins of this sort are a natural result of the changes of level that occur during mountain growth. Thus, there are extensive basins among the mountains of western United States, though, owing to the aridity of the climate, the lakes in the lower portions of these basins are small and shallow, and usually without outlets. Caspian Sea is in a basin that was probably formed by a down-warping of the surface, and it is thought by some geologists that change of level may be one of the causes for some of the Great Lakes of North America.

The formation of basins by crustal movement may be due either to folding or faulting (Fig. 216). Of the latter, Lake Warner and

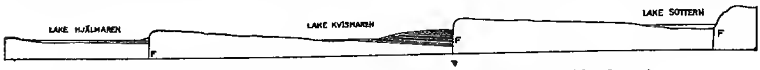


Fig. 216. — Swedish lakes in fault block depressions. (de Geer.)

other lakes in southern Oregon are examples, as is the Dead Sea, which lies in the bottom of a basin whose bottom has sunk between two faults. The chain of lakes in east-central Africa — including Tanganyika and Albert Nyanza — has been explained also as a result of down-faulting, forming what is called a *rift valley lake.*

Such movements of faulting and folding often give rise to large and deep basins; but there are also small ones of the same origin. Thus, near San Francisco there are small lakes and artificial reservoirs in a rift valley, where faulting occurred in the earthquake of 1906. Small lakes and ponds are not uncommonly caused by movements along fault lines during earthquakes or by the settling of portions of the surface. For instance, during the earthquake of 1819 in India, a portion of the delta of the Indus River settled, forming an inland sea 2000 square miles in area; and during the earthquake of 1811 in the Mississippi valley there was sinking of the bottom lands in northern Arkansas and neighbouring states, causing a number of lakes. One of these, Reelfoot Lake in Tennessee, is 20 miles long and 7 miles broad; it is said that here the fisherman's boat to-day floats over the submerged tops of cypress trees.

Without doubt, the most common cause for lakes is glacial action, for wherever glaciers have been there have been two processes in operation, as a result of which basins may be produced: (*a*) irregular erosion, (*b*) irregular deposition. We have already seen how important this cause for lakes has been, both in mountain regions where glaciers have recently been more extensive, and in areas of former continental glaciation. By erosion rock basins have been formed; by irregular deposition dams have been raised across stream courses; by irregularities in the moraine, the till sheet, and other glacial deposits basins have been made; and by the ice itself temporary dams have been formed, behind which lakes, often of large size, have gathered. There are a multitude of variations in the conditions under which such lake basins have been formed; and very often a combination of two of these causes has operated to form a basin. One of the most common conditions is that of erosion forming a rock basin and deposition raising the dam higher (Fig. 217), as in Seneca and Cayuga lakes in central New York, and in Lake Ontario. In the latter case warping may be a third cause coöperating to form the lake basin. One-twelfth of the surface of Sweden is covered by glacial lakes. Finland and

Fig. 217. — Lake Cayuga, New York, whose basin is due to glacial broadening and deepening of a river valley and glacial deposition at one end.

Canada are similar. In the lake district of northern Wisconsin 15 per cent of one county, which is five-sixths as large as the state of Rhode Island, is occupied by the waters of 346 small glacial lakes.

Another Classification of Lakes. — Lakes may be classified in other ways than the above. They may, for instance, be classified according to the cause which produced the dam, and this is a common classification. There are, for instance, (1) lakes due to land movements, or diastrophism, (2) lakes due to volcanic action, (3) lakes due to river processes, (4) lakes due to wave and tide work, (5) lakes due to wind action, (6) lakes due to glacial action. Each of these could be subdivided, but we will not follow classification further.

Stability of Lake Dams

The Destruction of Dams. — A lake dam may be of such loose material that it is easily washed away by the outlet current, and then the lake is lowered, and perhaps drained in a brief interval of time. It may happen that the dam is so weak that it is removed abruptly enough to precipitate the water of the lake suddenly into the outflow stream. Then even though the lake is of no great size, an appalling flood rushes down the stream. The bursting of artificial dams, as in the Johnstown flood (p. 107), has caused great destruction of life and property. A lake five miles long and seven hundred feet deep was formed in the upper Ganges in 1893 by an avalanche falling across a valley, and one year later the dam gave way and a flood of great destructiveness swept down the valley. Such dams are sometimes cut through by the streams, sometimes undermined by seepage, or, where made of soluble rock, by solution. In building artificial dams care must be taken to avoid the danger of wear at the top, seepage, solution, and erosion by pot hole action at the base of the dam.

Removal of Ice Dams. — Similar floods are caused by the sudden drainage of lakes held in by ice dams. This has been illustrated in the Alps, where small lakes thus impounded have found an outlet beneath the ice, and several instances are known in Alaska. Doubtless as the continental glaciers were receding there were numerous instances of floods, as the vast ice-dammed lakes fell from one level to another.

Erosion of Lake Outlets. — Where the dam is of greater stability, as where it consists of solid rock, the removal is far slower, and, were the destruction of lakes dependent upon the removal of the dam, it would be a far slower process than it is. Even though the volume of water is large, and the velocity is rapid, a lake outlet has little power of erosion, for it has been robbed of its cutting tools by sediment deposit in the quiet lake waters. Thus Niagara has done almost nothing toward lowering the level of Lake Erie, except to cut away unconsolidated drift; and the same is true of the St. Lawrence where it flows out of Lake Ontario. Here the current divides and subdivides among the Thousand Islands, not having cut deeply enough to establish a single channel. It is difficult to tell where the lake ends and the river begins. This is exceedingly immature drainage.

The Filling of Lakes

Rivers the Mortal Enemies of Lakes. — While some lakes are destroyed by the removal of the dam, and most lakes are lowered somewhat by cutting down at the outlet, it is not this action of the outlet stream that led Gilbert to state that "rivers are the mortal enemies of lakes." So long as a lake exists it is a temporary baselevel below which the inlet and tributary streams cannot cut their beds; it is also the receptacle for the sediment which the inflowing streams bear. Given time, even the deepest and largest lake will be exterminated by the deposit of the sediment that the streams bring into it.

Delta Growth in Lake Cayuga. — The rapidity with which this work is progressing is often easily inferred from the visible deposits of the inflowing streams. This may be illustrated by a specific case — Lake Cayuga in central New York. At the head an inlet and several tributary streams have built a delta three miles long, and a mile wide, filling the valley at the lake head from side to side, and extending out beneath the lake water till it ends in an abrupt slope. Each tributary stream that enters the sides of the lake is likewise building a delta, and the shoreline, therefore, has numerous projecting points, some of the largest being from a quarter to a half mile in the longest direction. Since its formation at the close of the Glacial Period, the area of Lake Cayuga has been diminished certainly by more than 5 square miles and perhaps twice that amount as a result of delta growth.

A larger illustration of the same thing is found in Lake Geneva, Switzerland. The muddy Rhone, fed by glacial streams, has a delta 20 miles long and built outward a mile in the 1900 years since Roman times. At the outlet of Lake Geneva the Rhone is clear, having had its sediment strained out in the delta-building of the inlet stream and the settling of the finer sediment on the lake bottom.

Lakes Bisected by Deltas. — Other lakes illustrate the same process, and in various stages, some, very recently formed or with little drainage, having but little filling; others partly filled; and some completely destroyed by filling. An intermediate stage of some interest is where deltas from opposite sides of a lake grow out toward each other and, finally meeting, divide a single lake into two lakes connected by a river-like channel. An early stage in this process is illustrated a few miles from the head of Lake Cayuga, where two deltas have each advanced a quarter of a mile or more toward each other. The completed stage is illustrated at the St. Mary Lakes of Glacier National Park, at Buttermere and Crummock Water in the English Lake District, and at Interlaken in Switzerland, where two lakes — Thun and Brienz — have been made by delta division of a former single lake.

Lake-bottom Deposits. — The visible delta is but a part of the process of lake filling by stream-borne sediment. Using Lake Cayuga again as illustration, after each period of heavy run-off, as when the winter snow melts rapidly, the lake water is discoloured with sediment far off shore from the stream mouth. Evidently, therefore, sediment is finding its way to the lake bottom beyond the delta front. Thus the lake is being shallowed, as well as narrowed by delta growth. We have no data for estimating the rate of shallowing, and in any event it would vary greatly from lake to lake. The steep front of the deltas indicates that the delta growth is the more rapid of these two causes for lake filling, though it must be remembered that the coarse delta deposit is localized, while the finer, suspended sediment is spread over a much wider area.

Other Mechanical Deposits. — Without doubt, stream-borne sediment is the chief factor in the filling of most lakes of sufficient size to have inlets or permanent tributaries; but it is not the sole cause. Rain wash drags sediment down slopes bordering lakes, as it does down other slopes; and from precipices weathering loosens fragments for gravity to pull down. Sediment from these sources is added to the accumulations that are filling lakes. The wind is also an agent of transportation of sediment to lakes. Another source of sediment is the beating of waves against the coast. This may cut the coast back and therefore enlarge the area of the lake. This is the case along parts of the southern shore of Lake Ontario, where the waves are rapidly cutting into drumlins that rise along the shore. But most of the material removed finds deposit on the lake bed, and therefore the process shallows the lake at the same time that it enlarges its area; and the volume of lake water displaced by deposit greatly exceeds that which spreads over the wave-cut bench, for the waves are consuming land that rises a hundred feet above lake level and depositing the débris off shore.

Organic Accumulations. — The filling of lakes is also aided by organisms. There are many shell-building animals and some plants that secrete lime or silica. The remains left upon the death of these organisms contributes materially toward the deposits that are filling the lakes. They help to fill the lakes by removal of some of the dissolved mineral load brought to the lakes by the rivers and underground water. In the shallow waters, and especially in the protected places, and in small lakes where good-sized waves cannot be formed, a luxuriant plant life thrives, including a variety of water-loving species. The remains of these plants, protected from rapid oxidation by the water, accumulate to form beds of plant remains.

Transformation to Swamps. — The last stage in the filling of a lake is often that of organic deposit, and in some cases where streams bring little or no sediment this is the main cause for the extinction of lakes. The lake water becomes more and more occupied by growing plants and plant remains, finally becoming a swamp; and this may later become high and dry enough for tree growth. Thousands of shallow lakes of glacial origin have thus been transformed to swamps in northern United States, Canada, and Europe. In some of the filled lakes occur layers of marl — calcareous remains of organisms and infusorial earth — silicious remains, both useful to man; and in the swamps are sometimes beds of bog iron ore, a deposit precipitated from percolating water by the influence of decaying vegetation. Though used in early days, and a possible reserve for the future, this source of iron is now of little use.

The Brief Life History of Lakes. — Since lakes are the depository of the sediment borne by the inflowing streams, their life history is necessarily brief, as geological time goes. They are, therefore, to be considered as recent phenomena of drainage. The length of time required for their extinction varies with the rate of accumulation and with the size of the lake. Already many small, shallow lakes formed by the continental ice sheet have been filled, and lava-dammed lakes near Mt. Shasta have been converted to meadows. Many others, like the Great Lakes, have gone but a short way on the road to extinction. Even the largest lakes, however, are doomed to ultimate destruction by filling, or by removal of the barrier, or by both combined; and the complete filling of even the Great Lakes would be reckoned as a brief task from the standpoint of geological time, or from the standpoint of the life history of a river valley. Lakes are merely episodes. Consequently, there are no lakes at present occupying basins which originated in early geological times; and where lakes exist we may be certain that they indicate either a youthful stage of drainage, or an accident to existing drainage, or the result of recent aggradation by the streams.

Removal of Lake Deposits

The Change in Stream Efficiency. — As long as a lake exists in a stream course it serves as a temporary baselevel; but when the lake is filled, or when it is drained by removal of the barriers, the streams can then flow across it as over any other land form. No longer being robbed of its sediment, the stream can more effectively cut into its bed along the course of the former outlet; and being no longer limited in its downcutting by the level of the standing lake water, the stream can sink its bed into the lake sediments. It will then proceed to remove the sediment burden temporarily deposited in the lake.

Meanders and Terraces on Lake Bottoms. — The removal of the lake sediments may be a very long process, — far longer than required to make the deposit. In fact, we have numerous cases of lake deposits of earlier geological ages, now transformed to solid rock and only partly removed. There are other cases where the streams have not yet begun the removal, but flow in meandering course over the filled lake. In the process of removal of these sediments the streams may develop a series of fine terraces as they swing back and forth, during downcutting in the unconsolidated lake deposits. Such terraces are to be seen at Bozeman, Mont. In the removal of lake sediments the streams behave as they do in other rock of similar texture and position.

Salt Lakes

Desiccation. — The removal of lakes by filling or cutting down of the barrier is a common mode of extinction of lakes; but, under some conditions, there is extinction by other processes, as by the recession of the dam, as a result of which marginal glacial lakes are sometimes exterminated. Another mode of extinction is by evaporation, or *desiccation.*

In all the continents there are areas where there is too little rainfall to fill basins to the point of outflow. There, as we have seen, salt lakes necessarily develop as the result of concentration of dissolved mineral matter. The regions where such lakes exist are regions of interior drainage; but if the climate becomes more moist, the basins may rise to overflow, or, if aridity sets in, the water level may sink below the outflow.

The Great Basin. — This succession of events has occurred in various parts of the earth, but the evidence of such changes has been most thoroughly worked out for parts of the Great Basin region of western United States. The Great Basin has an area of about 200,000 square miles of interior drainage, but it is not a single basin in any other sense than that it is, on the whole, a region lower than the mountains and plateaus round about. There are upwards of 60 separate basins in the Great Basin, each with streams entering it, and each without outlet. Some of these are high above sea level, and one, Death Valley, lies below sea level. In some of these basins salt lakes lie; in others there is standing water only at intervals.

The Region near Great Salt Lake. — In one of these basins lies the shallow Great Salt Lake, on a broad desert plain, with mountains rising above it. It has an area of about 2000 square miles, and an average depth of about 15 feet. The plain is evidently made of lake sediment, though its surface is in places crusted with salt and alkali. On the mountain sides is a succession of wave-cut cliffs and beaches, with such perfection of form that even the settlers recognized them as old shorelines (Fig. 218) before they were so interpreted by

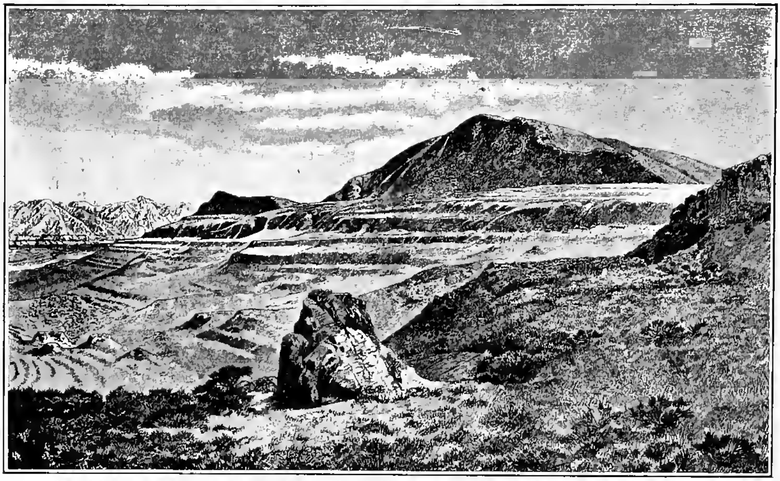


FIG. 218. — Beaches of Lake Bonneville, Oquirrh Range, Utah. (Gilbert.)

scientific study. It is evident that lake waters have risen to these levels; and an old outflow channel at Red Rock Pass is proof of former outflow. This channel, several hundred feet deep and a third of a mile wide, was occupied by a large-volumed stream.

Lake Bonneville. — At the time of overflow this great lake, called *Lake Bonneville*, had an area of 19,750 square miles and a depth at the deepest point of 1050 feet. Where the Mormon Temple stands, in Salt Lake City, the water was so deep that the temple would be under 850 feet of water if the old lake were restored. Not far from two hundred thousand people now live on the site of the extinct lake, and there are over 700 miles of railway there (Fig. 219).

A study of the physical features of the region and of the deposits, as interpreted by Gilbert, show that there was (1) an early period of long duration in which the climate was more arid than now. Then came (2) a period of rise of lake water, but not to the point of over-

FIG. 219. — Lake Bonneville, with the present Great Salt Lake in whitish tint near northeast corner. (Gilbert.)

flow. This lasted for a very long time. Following this was (3) a shorter period of aridity, then (4) a second rise to the point of overflow, followed by (5) the present period of aridity, the shortest of the three, and one that seems to be growing even more arid. During the overflow the lake was fresh water, the present saltness of the Great Salt Lake being the result of evaporation during the present period of desiccation. The basin in which Great Salt Lake is situated is merely a shallow depression in the sediments deposited on the bed of ancient Lake Bonneville. It is nowhere over 50 feet deep.

This basin, however, has been deeply filled during and before the Bonneville stage. Borings on the Lucia cut-off of the Union Pacific Railway show nearly 800 feet of clay, gypsum, and quicksand near the west coast of Great Salt Lake.

It cannot be exactly stated how long any one of the Bonneville stages persisted, though the evidence is clear that each had a duration of thousands of years. Nor can the cause for the climatic variations be given. There is reason for believing that the changes were accordant with the glacial and interglacial stages of the Glacial Period, the times of aridity coinciding with the interglacial stages, the times of humidity and lake rise with the glacial stages. One indication of the latter is the presence of moraines, showing that local glaciers extended into the lake during the expansion.

Lake Lahontan and Other Extinct Lakes. — Elsewhere in the Great Basin there has been a similar succession of lake rise and fall, notably in the case of extinct Lake Lahontan in Nevada. Shore lines around parts of interior basins in other continents tell a similar story of climatic change. Thus the history of lakes in arid regions, as well as of glacial phenomena in humid regions, testify to the fact that the climate of the earth is subject to notable change. From this testimony the conclusion seems warranted that the present is a period of relative aridity, as well as a period of relative shrinkage of glaciers.

Deposition in Salt Lakes. — When, through aridity, lakes shrink below the rim of the basin, the mineral load becomes more and more concentrated, but, with concentration, deposition necessarily follows. This is illustrated along the shores of Great Salt Lake, where carbonate of lime is being deposited in little rounded grains, called oölitic grains, giving the appearance of sand. In the shallow waters of Lake Mono calcareous tufa deposits are being made. This is because less carbonate of lime can be carried in solution in salt than in fresh water, and the carbonate of lime carried in by the land drainage is precipitated in the saline water. Gypsum, or sulphate of lime, is also precipitated, and even the salt cannot be carried in solution after a certain stage of concentration. Accordingly the shores and bottoms of very salt lakes may glisten with deposits of gypsum or salt, or both.

Salt lakes that have approached this stage are salter than the ocean waters, and their mineral-charged waters are so dense that one cannot sink in them. A bather in Great Salt Lake floats of necessity, and on emerging from the water a coat of salt crystals covers his body and clothes as the water evaporates in the dry air. It is estimated that there are 400,000,000 tons of salt dissolved in the waters of the Great Salt Lake, and the production of salt from its waters is an important industry, as it is around the shores of other salt lakes.

Bitter Lakes. — With further concentration the salt lake may become a "bitter lake," for other salts increase in relative percentage, notably the chloride of magnesium. With the increase in amount of the latter, common salt is precipitated. Thus in the Dead Sea there is nearly twice as much chloride of magnesium as common salt (chloride of sodium); but in the Great Salt Lake there is about eight times as much common salt as chloride of magnesium. As evaporation continues, however, more and more of the common salt will be deposited, and the water will become more bitter.

It seems possible that some lakes are fresh merely because they are new. Thus the Dead Sea and Great Salt Lake are known to have originally been fresh. If we compare the salinity of several lakes — (*a*) Great Salt Lake, 18 per cent, (*b*) the Dead Sea, 24 per cent, (*c*) Lake Van, 33 per cent, and (*d*) a saline — it is clear that these enclosed seas are progressively becoming salter. Salt lakes like the Caspian Sea, which were originally part of the ocean, do not fall in this class. The latter has been freshened by river waters till it is less saline than the ocean.

Formation of Salt and Gypsum. — In arid regions there are dried-up salt lakes where deposits of salt, gypsum, and other minerals are found. Similar deposits, formed in earlier geological times, are now found even in humid regions, stratified with the sedimentary rocks, and are an important source of salt, gypsum, and other mineral substances of value.

Playa Lakes. — Basins of salt lakes, even though the water does not rise to the point of overflow, are nevertheless being slowly filled. The streams that enter the basins leave their sediment in them, as we have seen. The winds add other deposits, while precipitation of dissolved mineral aids still further in the filling. These processes are very often seen where streams, extending out from bordering mountains, wither at their lower ends by evaporation and by sinking into the sediment that they have brought to their alluvial fans. Now and then the withered stream is given such a volume that its waters extend on to the bottom of the basin, there forming a temporary lake, or, as it is called in western United States, a *playa lake.* When the supply of water ceases, the playa lake shrinks and finally disappears by evaporation, but its site is marked by alkali deposit where the dissolved mineral has been precipitated and later baked and cracked in the sun.

Alkaline Soil. — Alkali flats are unsuited to most kinds of plant growth and are, therefore, valueless for agriculture. Salt and alkali are sometimes disseminated through the soil of arid regions, and streams are even impregnated with them. Such alkaline water, spread out upon fields in the process of irrigation, may leave a deposit which is fatal to agriculture; and even where the water used in irrigation is free from alkali, if there is any in the soil, it may rise to the irrigated surface and unfit the land for raising crops.

The Great Lakes

The World's Largest Lakes. — The five Great Lakes of the United States and Canada form the greatest group of lakes in the world. They have had a profound influence on the development of both these countries. Their combined area is about 95,000 square miles, or more than the total area of the island of Great Britain. Various facts concerning these lakes are given in the accompanying table, compiled by Vedel. This does not include the other large bodies of water, Lakes Winnipeg, Athabasca, Great Slave and Great Bear to the northwest outside the St. Lawrence drainage system, although the last two are larger than Lake Erie.

Name of Division of Great Lakes System	Length, Miles	Average Width, Miles	Maximum Width, Miles	Shore Line, Miles	Water Area (including Islands) Square Miles	Average Depth, Feet	Maximum Depth Sounded, Feet	Surface above Tide-water, Feet	Deepest Point above Tide-water, Feet	Water Volume, Cubic Miles	Land Area of Water Shed, Square Miles	Aggregate Water and Land Area of Water Shed, Square Miles
Lake Superior .	390	70	160	1300	31200	475	1008	602	− 406	2800	51600	82800
St. Mary's River .	53 / 40	2½ / 2	5 / 4	100	200	—	53	—	—	—	800	1000
Lake Michigan .	335	58	85	875	20200	335	870	581	− 289	1290		
Green Bay . . .	115	15	21	260	1700	95	144	581	+ 437	30	37700	60100
Mackinac Strait .	30	16	23	60	500	75	234	581	+ 347	7		
North Channel .	110	12	18	220	1400	70	240	581	+ 341	20		
Lake Huron .	250	54	100	725	17400	210	702	581	− 121	650	31700	55700
Georgian Bay . .	120	40	58	390	5200	170	462	581	+ 119	170		
St. Clair River .	35	1	—	70	30	—	—	—	—	—	3800	3830
Lake St. Clair . .	19	25	29	90	410	—	21	575	+ 554	1	3400	3810
Detroit River .	27	2	3½	54	60	—	—	—	—	—	1200	1260
Lake Erie . .	25	40	58	590	10000	70	204	573	+ 369	130	22700	32700
Niagara River . .	34	1	2	70	60	—	—	—	—	—	300	360
Lake Ontario . .	180	40	58	600	7300	300	738	247	− 491	410	21600	28900
St. Lawrence River	760	20	95	—	—	—	—	—	—	—	—	—
Totals .				5404	95660					5508	174800	270460

Water Content. — The rainfall of the region of the Great Lakes averages about 31 inches per year, and this suffices to fill the basins and cause a discharge of about 86,000 cubic feet per second from Lake Superior, 225,000 cubic feet from Michigan and Huron, 265,000 cubic feet from Erie, and 300,000 cubic feet per second from Lake Ontario. The aggregate discharge is double that of the Ohio River, and nearly half that of the Mississippi.

Over half of the water in the Great Lakes is in Lake Superior, which is both the deepest and by far the largest of the lakes. It has been estimated that the amount of water in the Great Lakes is sufficient to sustain Niagara Falls in the present condition for about 100 years.

The Lakes and Rapids. — The lakes are a series of boat-shaped basins with their long axes pointing in different directions, so that they penetrate a wide area of country and bring it within reach of this great, navigable, interior waterway. From the great deep basin of Lake Superior, the elevation of whose surface is 602 feet, there is a descent to the basins of Lakes Michigan and Huron, whose surfaces lie 581 feet above sea level. The main descent is in the rapids of Sault Ste. Marie. Huron and Michigan are on the same level, and the surface of Erie is but eight feet lower. Between Lake Erie, whose surface lies at an elevation of 573 feet, there is a great descent to Ontario, whose surface is only 247 feet above the sea, the greater portion of this descent occurring at the Niagara cataract. Below Lake Ontario the St. Lawrence consists of alternate, lake-like expanses and rapids, and the greater part of its total fall of 247 feet is accomplished in a few narrow stretches of rapids. The rapids and falls in this waterway have been serious obstacles to navigation, though the building of canals, especially by the Canadians, has done much to overcome the effects of the obstacles. Now large boats may go up the St. Lawrence to the western end of Lake Superior by river, canal, and lake; and smaller boats may go from the Hudson to Lakes Ontario and Erie by canal.

The Problem of Origin. — The question of the origin of these basins is one of great interest, but one which cannot as yet be answered with certainty. There is abundant reason for the conclusion that the lakes did not exist before the Glacial Period, and, as has been stated in preceding pages, there has apparently been a combination of three causes operating to produce the basins: (1) local warping or tilting of the earth's crust, (2) glacial erosion, (3) glacial deposit across preëxisting valleys. The relative value to be placed upon these three causes has not been demonstrated, and it is quite probable that a different relative value will be found for the different basins. Nor can the relative value of the work of the different ice sheets be stated. There are buried gorges in the Great Lakes region, and these are more or less filled with drift. The mistake has been made of considering all such gorges as preglacial stream courses, whereas it is far more probable that at least some of them are interglacial gorges.

St. Lawrence System Abnormal. — The St. Lawrence system seems to be not a normal stream system, but a composite of parts of several. A normal stream system should show a general gradation from source to mouth. But the St. Lawrence shows this condition for a distance above Montreal; then, above that, there is an absolute lack of it. At the Thousand Islands there is no valley, but the river flows on the surface of a low, hilly land, drowning the shallow valleys.

Above, comes a broad, deep, boat-shaped basin, but there is no continuation of this either toward Lake Erie or toward Georgian Bay, for buried gorges, probably of interglacial age, are no true continuation of such a basin as that of Lake Ontario. A similar statement is true of the relation of the other lakes to those above or below.

The Great Lakes are anomalous forms of drainage, being a series of basins of different shapes and depths, connected by straits or rivers which are quite out of harmony with the basins in depth and width. Moreover, though forming a part of a great river system, the Great Lakes have a peculiarly narrow and irregular divide. Sometimes the divide comes down almost to the lake shore, and nowhere is it very far distant. There is no regular variation, the divide of Lake Ontario, for instance, being no farther away from the lake than that of Lake Superior. The bottoms of some of the lake basins are far below sea level, which is abnormal in a drainage system.

Theories of Origin. — These anomalies have been generally recognized by all who have written on the subject, and, in explanation of them, one theory has been based upon the attempt to reconstruct the preglacial drainage along essentially the line of the present-day basins, assigning the anomalies primarily to warping. Another theory has been that before the Glacial Period streams flowed in different directions, some going to the Mississippi, some possibly to the Arctic or toward the east. By glacial erosion, glacial deposition, and warping of the land, in relative amounts not determined, basins were formed, and when the ice disappeared, drainage from one to the other followed along lines quite independent of preglacial drainage, giving rise to the present peculiar lake system. That the lakes and their drainage were different in form and direction during interglacial time is probable, though not proved.

This is as much as can at present be said upon the basis of existing evidence regarding the origin of these basins; and interpretations that pretend to be more exact are misleading. That further careful study may make possible a more definite statement of the origin of the Great Lakes is to be expected. It will, however, in all probability involve four elements: (*a*) glacial erosion, (*b*) glacial deposit, (*c*) warping, (*d*) diversion of preëxisting drainage. But what relative weight will ultimately be placed upon each of these four elements cannot now be safely predicted. Some students of the subject, including the author, believe it probable that glacial erosion will be proved to be the leading factor.

Movements of Lake Waters

Currents near Inlets and Outlet. — Although the lake water has been spoken of as standing water, it is not to be considered as actually motionless. There is a current opposite the mouth of each inflowing stream, and a current must of necessity set toward the outlet; but out in the central part of a large lake such movements are practically negligible.

Effect of Temperature Changes. — A far more important cause for movement of lake water is that resulting from change of temperature, and, therefore, of density. As the temperature at the surface descends, the water becomes denser, and, being then heavier, it settles, displacing the water below. Thus a vertical circulation is set up, cold dense water sinking, and warm, lighter water rising. In fresh water this continues until 39° F. (4° C.) is reached, after which settling ceases, because this is the point of greatest density of fresh water. As a result of this circulation the temperature of the bottom water of good-sized lakes in regions having cold winters is low, even throughout the summer. It approaches 39°, though usually it is a few degrees above this point.

Effect of Winds. — The winds are another important cause for a circulation of lake waters. They not only set the water into undulation, forming waves, but, by the friction of the moving air, a drift of water is started in the direction toward which the air is moving. After a day of steady wind there is a perceptible drift, and it may continue for hours after the wind dies down, being noticeable by the slow drifting of floating bodies, and by the heaping up of water at one end of a long lake (p. 309).

It has been observed on Lake Cayuga that when strong winds blow from the south, even though they are warm winds, the water at the southern end of the lake is colder than normal. This is due to the fact that the warm surface water is drifted northward, giving rise to an increase in the height of the water toward the north and a decrease in height at the southern end. The higher column of water to the north presses downward and forces a southward flow of the lower, colder water to equalize the pressure, and this cold water even rises to the surface. Thus the wind causes not only a circulation at the surface, but also a movement involving layers below the surface. This is probably the explanation of the fact that the bottom waters of deep lakes are not at the temperature of the maximum density of water.

Lake Currents. — In very large lakes, like the Great Lakes, a fairly definite set of currents is established, primarily by the wind. This is illustrated for the Great Lakes in the accompanying map (Fig. 220). The strength of the currents varies, and even their direction is not uniform from day to day, but there is an average set of surface waters approximately as indicated. Doubtless the circulation is actually much more complex than indicated; and doubtless, also, there is a vertical circulation as well as the horizontal movement of the surface layers. The general eastward trend of the waters is a result of the fact that the wind direction averages from a westerly quadrant. As previously noted the drift of water toward the outlet end of a lake augments the volume of the outlet stream, and a movement in

FIG. 220. — The currents in the Great Lakes. (After Harrington.)

the opposite direction diminishes the volume. Notable fluctuations in the volume of Niagara River are sometimes caused in this way.

Minute Tides in Lakes. — Minute tides are generated in very large lakes and, on quiet days, may be measured by delicate instruments. They become especially noticeable when concentrated in narrowing bays. A tide of about 3 inches is reported at the southern end of Lake Michigan and at the western end of Lake Superior.

Seiches. — Much more noticeable than this is an irregular rise and fall of the lake water known as *seiches*, studied especially in Lake Geneva in Switzerland, but noticeable on most, if not all, large lakes. During the seiches the lake waters rise and fall in a rhythmic swing, with a movement somewhat like that which can be caused by tipping a basin of water back and forth. The phenomenon of seiches is due usually, if not always, to decided differences in atmospheric pressure on different parts of the lake. The atmosphere exerts a certain pressure on the lake water, which at sea level is approximately 15 pounds per square inch. If a storm passes over the lake, the pressure at this point may be notably lessened, while all around it remains as it was. In that case the surface of the lake will rise beneath the area of low pressure; or, if it be a high-pressure area, the lake surface will be lowered by the extra pressure of the air. This disturbance of the lake level is in the nature of a wave, and it may sweep across the lake from end to end, and even traverse the lake back and forth for several times before dying out.

Lake Shores

Likeness to Ocean Coasts. — In their more general features lake and ocean shores are so nearly alike that they may be discussed together. Both, for example, are modified by wave attack, with the resulting development of wave-cut cliffs and wave-built beaches of various forms. Both are influenced by currents, and in both cases there is a rise and fall of the water surface, though in lakes this is less rhythmic and less important than the tidal rise and fall of many oceanic coasts. Naturally the resemblances become greatest in the shorelines of large lakes, and a study of such a lake shore gives ample basis for an interpretation of many of the fundamental elements of ocean shore features. Therefore, in the succeeding chapter (p. 342), where shorelines are treated specifically, both lake and ocean shorelines are included.

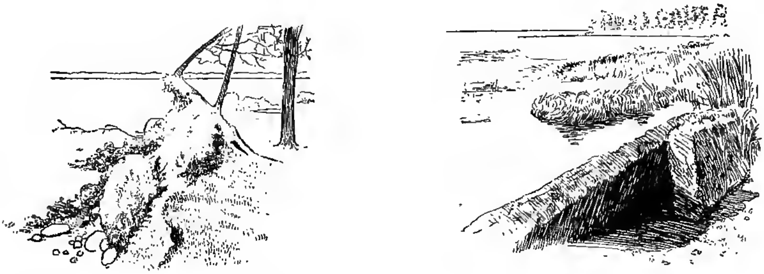
Contrasts with Ocean Coasts. — There are, however, some directions in which lake shorelines differ from ocean coast lines to a greater or less degree. Ordinarily lake shorelines are less intensively developed, for the agents are less intense; but there are many bays along the ocean in which there is far less intense work than along the coast of the Great Lakes. Tidal currents, locally important along ocean shores, find no equivalent in lakes.

The work of organisms is wholly different in the two bodies of water. There are, for instance, no coral reefs along lake shores, and the effect of fresh-water plants is quite different from that of salt-water plants. Very often the shores of small lakes and ponds are completely under the domination of plant growth. By different species of plants this condition is imitated in protected bays along ocean coasts though with different kinds of plants.

Larger Deltas in Lakes. — Lake shores are commonly the seat of more pronounced deposition than ocean shores, for the sediment poured into them is less widely distributed. For this reason delta points project from lake shorelines opposite the stream mouths far more commonly than on the ocean coast, and their form is not the same. Here again, however, this is less true of the very large lakes, and there is a close resemblance between lakes and ocean bays in this respect.

Ice Ramparts and Boulder Pavements. — The work of ice along lake margins is different from that along most ocean coasts, though resembling that of the frigid zones and of bays that freeze over in the cold temperate regions. The effect of ice along the shores of ponds is often very pronounced. By it ridges of gravel are often piled up along the coast, forming *ice ramparts* (Fig. 221), and boulders are shoved slowly up the beach, often forming a *boulder pavement.*

Some of this ice work is performed by the ice hurled against the coast by waves, but much of it is the direct result of the powerful shove



of the ice cover of the frozen pond or lake. As the ice is formed it expands, and a lateral thrust may result. When the temperature descends, the ice contracts, and cracks open in which freezing takes place, exerting a further lateral thrust. If then the temperature rises, the ice expands and other thrust is applied. By these thrusts sufficient force is applied to push along even good-sized boulders. Since the process is repeated winter after winter, a considerable movement may eventually result.

Fig. 221. — Ice ramparts in Lake Mendota, Wisconsin. (After Buckley.)

Lake Shores more like Ocean Bays. — From this it is clear that lake shorelines bear a close resemblance to ocean shorelines, but that there is closer resemblance between the shores of ocean bays and lakes. Only in relatively unimportant details are there differences. That this is true is indicated by the fact that the shoreline of the extinct glacial lake south of Lake Ontario and the one in the Lake Superior basin has been interpreted as an ocean shoreline by at least one observer.

Importance of Lakes

The Water covers Arable Land. — Whether lakes really return more to man in the various uses to which they are put than would be returned if their area were dry land, upon which farming and other industries could be carried on, is an academic question, and one upon which no certain answer can be given. Doubtless the answer would be different in different cases. In Sweden, for instance, where one-twelfth of the surface is lake, this is undoubtedly true, for many of the lakes are now of little service. The site of a large lake at Ragunda, accidentally drained in 1796 by the diversion of the outlet, has become the seat of many valuable farms, and, without doubt, the products of these farms far exceed the value of the lake. Whether the drainage of the Great Lakes, even though they cover an area of 95,000 square miles of possibly arable land, would be an economic advantage is exceedingly doubtful.

Man's Uses of Lakes. — Lakes are of service to man in numerous ways. (1) They store water useful for (*a*) regulating stream volume; (*b*) supplying water for city drinking supply, as at Chicago; (*c*) supplying water for factories; (*d*) furnishing water for irrigation. (2) They are an important source of food fish. (3) From the surfaces of lakes ice is cut for many uses. (4) As resorts, for health and pleasure, lakes possess a high value to mankind. They may even be sought for protection, as by the ancient lake dwellers of Venezuela. (5) The larger lakes are highways of navigation, especially well illustrated in the case of the Great Lakes, one of the world's busiest highways, and so important that they have been a large factor in the location and growth of a number of large cities, — Buffalo, Cleveland, Detroit, Chicago, Milwaukee, Duluth, Superior, and others. (6) Lakes exert a powerful influence upon local climate.

Influence on Climate. — The influence of lakes upon local climate is illustrated even by small lakes, which cool the air in summer and warm it in winter if their surface is not frozen over. Where lakes are numerous, as in Sweden or Finland, the large expanse of lake water must exert a very notable influence, both upon the temperature and the humidity of the air. Large lakes are still more important. This is well illustrated by the Great Lakes, from whose vast expanse the winds must receive much vapour, and must have their temperature greatly modified. It is due to the influence on temperature that fruit raising is such an important industry in the neighbourhood of some of the Great Lakes. On the peninsula of Ontario, for instance, between Lakes Ontario and Erie on the one side and Lake Huron on the other, grapes, peaches, and other fruits, and even tobacco, are extensively raised. The peninsula of Michigan, between Lakes Huron and Michigan, is a noted fruit region, but the west shore of Lake Michigan in Wisconsin is less favourable because the prevailing winds are toward the lake, not from it. The shores of both Lakes Erie and Ontario are favourable to fruit raising.

In the grape district along the southern shore of Lake Erie the growing season is lengthened by the effect of the lake waters in retarding the cooling of the air during times of frost. Thus late frosts in spring and early frosts in autumn are less common near the lake than at a distance from it. In lake valleys, such as those of Seneca and Keuka lakes, the air temperature is greatly modified by the water, and grape raising is an important industry. This influence is often clearly illustrated in the neighbouring Lake Cayuga valley, when the snows completely melt from the lower valley slopes while the hills are still white;

and farmers, coming from the upland to the valley in sleighs, find bare ground when they are only two or three hundred feet above the city in the valley bottom.

Lakes as Barriers. — Great lakes are often barriers, resulting in the necessity of man making detours in road and railway building, although the lake may be used as a highway of commerce by steamer, freight by water being cheaper. The railways are forced to swing far southward through Chicago, because Lakes Erie and Michigan make a direct line from Buffalo to St. Paul impossible. Long, narrow lakes, however, may be bridged. Car ferries are operated on Lake Michigan between Wisconsin and Michigan. Lake Baikal on the Trans-Siberian Railway was crossed by a line laid over the ice in winter and by car ferry in summer before the expensive line around its south end was built. Great Salt Lake was crossed by a line, the Lucin cut-off, built on piling and filling for over 25 miles in this broad, shallow lake to avoid the long, crooked, original line around the north end of the lake (Fig. 222).

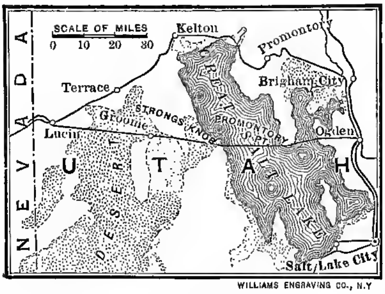


Fig. 222. — The railway crossing Great Salt Lake at Lucin cut-off.

Extent and Value of Swamps

Nature of Swamps. — A swamp is a part of the surface of the land which is wet and saturated with moisture, though not usually covered with standing water. Some swamps are called *marshes*, *bogs*, or *muskegs*. At least a part of the Arctic *tundra* is also swamp, especially in summer when the frozen surface soil thaws. There is every gradation between swamps and lakes and between swampy and dry land. In this intermediate class are areas which are swampy only during a part of the year; and many swamps are covered by a thin sheet of standing water during seasons of heavy rain or rapidly melting snows.

Uses to Man. — Swamps are of great importance to man, for they cover enormous areas, and, until drained, are of little value. It is estimated that there are in the United States 79 million acres of swamp and marsh land, equal to the combined areas of the states of Ohio, Indiana, and Illinois, or of Great Britain and Ireland. This is largely waste land in its present state, though some of it has timber growth, some is utilized for rice or cranberry culture, and some is occupied by cattle for a part of the year. When drained, however, such land often makes excellent farm land, for the surface is level, and the abundant humus in the swamp deposit favours the growth of many crops.

Drainage of Swamps. — Some swamp land is readily drained by simple means, such as the use of tiles for underground drainage, and that method has been employed extensively in the reclamation of the swampy prairie areas of the Central States. Here the fertile soil owes its black colour to the swamp vegetation that flourished before the artificial drainage. In some cases only the removal of vegetation is necessary to drain a swamp, for the dense growth of grass or forest may so interfere with the run-off of water from level land as to make it swampy land, at least for a part of the year.

Reclaimed Swamps in Europe. — Other swamps can be drained only by means of ditches, and sometimes by a complex and expensive system of ditches and drainage canals. This has been much done in Europe, where for many generations the land has been so fully occupied that it has paid to reclaim waste land, even at the expense of much labour. There are tracts of such reclaimed swamp land in England; a part of Holland is reclaimed floodplain swamp; and there are extensive tracts of reclaimed swamp land in Germany. An instance of the latter is in the Spreewold district, not far from Berlin, where a swampy tract along the Spree River has been reclaimed by the digging of a multitude of canals and ditches, and the quaint people who dwell there go to their fields, to church, and to school, not over the land, but by boat along the drainage canals.

The Swamp Resource in United States. — In the United States little has so far been done toward drainage of the more expensive type, for as yet land has been plentiful and cheap. But the time is at hand when the reclamation of some of these waste areas must be undertaken. This is important not alone from the standpoint of the increase in the area of farm land, but also from the standpoint of health. The damp swamp lands are unhealthful, and often the breeding place of mosquitoes, which spread malaria well beyond the limits of the swamp. Along the swampy bottom lands of the Arkansas and lower Mississippi rivers, for example, the people are cursed with "fever and ague"; and many a town in the north also suffers from malaria as a direct result of the close neighbourhood of mosquito-breeding swamp tracts.

Much fertile land can be added to the farm acreage of the United States by adequate drainage and protection from overflow, and a vast saving be made in human life also. It has been estimated that 77 million acres of the swamps in the United States can be drained at nominal cost, resulting in an increase in value of 2849 million dollars.

Kinds of Swamps

Influence of Levelness and Impervious Soil. — The cause of swamps is the inability of water to run off or percolate into the ground rapidly enough to drain the land. This implies levelness of surface and either a state of permanent saturation of the ground or such a degree of imperviousness as to interfere with rapid percolation. Thus a sandy area of level ground will not become a swamp as readily as a level clay area; but even a sandy tract of level land below the water table will become a swamp.

Swamps on Coastal Plains. — Any cause which will produce a level surface introduces the prime condition necessary to swamp development when water is added. Such a cause is the uplifting of a level sea bottom, forming a coastal plain, and this accounts for the great development of swamps along the southern coast of the United States, from Virginia to Texas, including the Everglades of Florida (5000 square miles) and the Dismal Swamp of Virginia and North Carolina. There are thousands of square miles of swamp land on this coastal plain, mostly now waste land, but much of it capable of drainage.

Swamps in River Valleys. — Another important cause for level land is river deposit, forming floodplains and deltas; also, by natural levees, or by deposit of silt at river mouths, making obstacles to the run-off of water. Consequently rivers on floodplains and deltas are commonly bordered by swamps (Pl. III). It is estimated that along the lower Mississippi there is a tract of land subject to overflow equal in area to the entire state of South Carolina or 30,000 square miles.

Influence of Vegetation. — Swampiness depends upon the rates of (*a*) run-off, (*b*) percolation, (*c*) evaporation, and (*d*) on the volume of water supplied. Given a certain volume, the rate of run-off is governed by the slope and the amount of vegetation. The influence of vegetation in checking run-off is very great, and many swamps are due to this influence alone, while the area of others is enlarged by it. This is true, for instance, of Dismal Swamp in Virginia and North Carolina, and doubtless of many other of the coastal plain swamps. It is one of the reasons for swampiness in the tropical zone, where heat and dampness encourage luxuriant plant growth. With the development of the swampy condition, plant growth is encouraged by the dampness, and hence swamp development is still further aided. Reeds, cane, and other plants thrive, and even trees adapt themselves to growth in persistently wet lands. Notable among these are the cyprus and black gum, the former sending projections from their roots upward above the swamp level in order to insure the necessary air, the latter having arches in the roots which accomplish the same purpose.

Percolation is governed by the porosity of the soil and the level of the water table. Evaporation varies with the dryness of the air and the amount of wind to remove the vapour. A vegetation cover checks evaporation and in that way also encourages swampiness; but it operates in the opposite direction by removal of water to build into the plant tissue, and to give out to the air by transpiration. Water volume depends solely upon the rainfall in many swamps, but in river swamps it is partly, or even largely, supplied by river flow. This cause greatly increases the area of permanent swamps along rivers, and even further increases the area of temporary swampiness which succeeds each overflow until run-off, evaporation, and percolation can dry out the wet soil.

Swamps in Arid Lands. — Arid lands and deserts are not notable for swamp areas, for although there is level land, there is light rainfall, rapid percolation, rapid evaporation, and such an absence of vegetation that run-off is little checked by that cause. Swamps in such regions are mainly confined to the river courses and to the evaporated lakes at the terminus of intermittent streams. Alkali flats and *salinas* are a desert form of swamp.

Swamps in the Tropics. — Tropical countries of heavy rainfall are especially favourable to swamp development, for there is abundant water supply, the water table is high in so damp a climate, and percolation is, therefore, reduced. The air is so humid that evaporation is at the minimum, and vegetation growth is so luxuriant that the interference with run-off is at the maximum. This swampiness is one of the prime reasons why malaria and other diseases make living in the tropical zone so hazardous.

Swamps due to Glaciation. — Glaciated regions are the seat of innumerable swamps, partly because level tracts were made by glacial deposit, and partly because shallow lakes of glacial origin have been partially or completely filled since formation. In the course of lake filling, as we have seen, vegetation is of much importance in the final stages, and ultimately the site of the lake becomes a swampy plain.

Swamps in Cool, Northern Lands. — In the cool, northern climate the assemblage of plants growing in the shallow lakes and swamps is different from that of the warmer, southern regions. Among the plants there is one of such dominant importance as to call for special mention, namely, the *sphagnum moss*. It grows luxuriantly in northern Europe and United States, and in Canada, and takes an active part in the late stages of lake filling, forming sphagnum bogs.

Quaking Bogs. — Sphagnum will grow outward, even on the surface of shallow ponds, and sometimes cover the surface, while beneath is a miry liquid, part water, part decaying vegetation (Fig. 223). Walking upon such a surface results in a shaking like jelly, giving rise to the name *quaking bog*. From the bogs of Ireland and other regions the bodies of men and animals are sometimes excavated, showing the danger that may result in trusting to such an unstable surface. The acids of the decaying vegetation have a preservative effect, and such remains are often in a remarkable state of preservation.

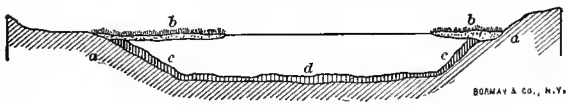


FIG. 223. — Cross-section of a lake being filled by sphagnum moss, *bb*, and muck from its decay, *cdc*, converting the lake into a quaking bog. (Shaler.)

Climbing and Bursting Bogs. — Sphagnum is sponge-like, and it is able to grow even on slopes, taking up and retaining water. In damp climates, like Ireland, it may grow even on hillslopes, forming *climbing bogs*, and similar bogs occur on slopes in the United States where springs, emerging from the hillside, supply the necessary water. In Ireland they grow to such size and on such slopes that, becoming charged with water, they sometimes slide down the slope. Such *bursting bogs* sometimes destroy both life and property.

Relation of Swamps to Formation of Coal. — In Ireland, Scotland, Scandinavia, north Germany, and other parts of northern Europe, the

FIG. 224. — An Irish bog, where peat is being excavated for fuel.

sphagnum bogs are an important source of fuel for local use (Fig. 224); in North America, although there are hundreds of square miles of sphagnum bog, it is as yet practically unused. In the sphagnum bogs, and in the swamps of the more southern regions, such as Florida, we see a first stage in coal formation, though with entirely different plant assemblages. The coal swamps probably developed on level coastal plains, the vegetation grew luxuriantly, and extensive deposits of plant remains accumulated, protected from decay by the dampness, and, as in Florida, there was little admixture of sediment. Then came submergence and deposit of sediment, and the layer of plant remains became incorporated in the strata and started on the slow series of changes by which it changed to the mineral coal. Submergence of Florida, or of Ireland, beneath the sea would carry the swamp deposits one step farther toward the stage of mineral coal, and after the lapse of sufficient time they would become seams of coal, bedded between other kinds of rocks, just as is the case in the coal beds now mined.

References to Literature.

Louis Agassiz. Lake Superior, Its Physical Character, Vegetation, and Animals, Boston, 1850, 428 pp.

E. A. Birge. The Respiration of an Inland Lake, Pop. Sci. Monthly, Vol. 72, 1908, pp. 337–351.

E. A. Birge and C. Juday. The Inland Lakes of Wisconsin (Dissolved Gases), Bull. 22, Wis. Geol. Survey, 1911, 259 pp.

A. P. Brigham. Lakes, a Study for Teachers, Journ. School Geog., Vol. 1, 1897, pp. 65–72.

E. R. Buckley. Ice Ramparts, Trans. Wis. Acad., Vol. 13, 1900, pp. 141–162.

F. W. Clarke. The Waters of Closed Basins, Data of Geochemistry, 2d edition, Bull. 491, U. S. Geol. Survey, 1911, pp. 143–167.

C. A. Davis. A Contribution to the Natural History of Marl, Journ. Geol., Vol. 8, 1900, pp. 485–497; *ibid.*, pp. 498–503; *ibid.*, Vol. 9, 1901, pp. 491–506.

W. M. Davis. On the Classification of Lake Basins, Proc. Bost. Soc. Nat. Hist., Vol. 21, 1883, pp. 315–381; The Classification of Lakes, Science, Vol. 10, 1887, pp. 142–143.

A. Delebecque. Les Lacs Français, Paris, 1898, 436 pp.

N. M. Fenneman. Lakes of Southeastern Wisconsin, Bull. 8, Wis. Geol. Survey, 1902, 1910, 178 pp.

R. Follansbee and A. C. True. Swamp and Overflow Lands, Rept. Nat. Conservation Commission, Vol. 3, 1909, pp. 361–374.

F. A. Forel. Le Léman, Lausanne, 3 vols., 1892 to 1904, 538, 651, 715 pp; for the seiches, see Compte Rendu, Vols. LXXX, 1875, p. 107; LXXXIII, 1876, p. 712; LXXXVI, 1878, p. 1500; LXXXIX, 1879, p. 493.

M. L. Fuller. Sunk Lands, Bull. 494, U. S. Geol. Survey, 1912, pp. 64–75.

G. K. Gilbert. Lake Bonneville, Monograph 1, U. S. Geol. Survey, 1890, 438 pp.; Lake Bonneville, 2d Ann. Rept., U. S. Geol. Survey, 1882, pp. 167–200.

M. W. Harrington. Surface Currents of the Great Lakes, Bull. B, U. S. Weather Bureau, 1895.

W. H. Hobbs. A Study of Lake Basins, Earth Features and their Meaning, New York, 1912, pp. 401–434.

C. Juday. The Inland Lakes of Wisconsin (Hydrography and Morphology), Bull. 27, Wis. Geol. Survey, 1914, 137 pp.

G. D. Louderback. Lake Tahoe, California-Nevada, Journ. Geog., Vol. 9, 1911, pp. 277–279.

Lawrence Martin. The Basin of Lake Superior, Monograph 52, U. S. Geol. Survey, 1911, pp. 110–117; The Progressive Development of Resources in the Lake Superior Region, Bull. Amer. Geog. Soc., Vol. 43, 1911, pp. 561–572, 659–669.

H. R. Mill. Bathymetric Survey of the English Lakes, Geog. Journ., Vol. 6, 1895, pp. 46–73, 135–166.

J. Murray and L. Puller. Bathymetrical Survey of the Scottish Fresh-water Lochs, 2 vols., Edinburgh, 1910.

C. Rabot. Revue de Limnologie, La Géographie, Vol. 4, 1901, pp. 110–119.

A. C. Ramsay and Others. Upon the Origin of Alpine and Italian Lakes, New York, 1889, 148 pp.

I. C. Russell. Lakes of North America, Boston, 1895; Present and Extinct Lakes of Nevada, National Geographic Monographs, New York, 1896, pp. 101–136; Lake Lahontan, 3d Ann. Rept., U. S. Geol. Survey, 1883, pp. 189–235; Lake Lahontan, Monograph 11, U. S. Geol. Survey, 1885, 288 pp.; Mono Lake Region, 8th Ann. Rept., U. S. Geol. Survey, Part 1, 1889, pp. 267–319.

E. H. Sellards. The Florida Lakes and Lake Basins, 3d Ann. Rept., Florida Geol. Survey, 1910, pp. 47–76.

N. S. Shaler. On the Origin of the Excavated Lake Basins of New England, Proc. Bost. Soc. Nat. Hist., Vol. 10, 1866, pp. 358–366; Sea Coast Swamps of the Eastern United States, 6th Ann. Rept., U. S. Geol. Survey, 1885, pp. 353–398; General Account of the Fresh Water Morasses of the United States, 10th Ann. Rept., U. S. Geol. Survey, Part 1, 1890, pp. 255–339; Beaches and Tidal Marshes of the Atlantic Coast, National Geographic Monographs, New York, 1896, pp. 137–168.

R. S. Tarr. Physical Geography of New York State, Chapter VI, New York, 1902.

J. B. Tyrrell. The Genesis of Lake Agassiz, Journ. Geol., Vol. 4, 1896, pp. 811–815.

A. C. Veatch. Formation and Destruction of Lakes of Red River Valley, Prof. Paper 46, U. S. Geol. Survey, 1906, pp. 15, 60–66.

P. Vedel. Facts about the Great Lakes, Amer. Geol., Vol. 18, 1896, p. 196.

T. L. Watson. Lakes with More than One Outlet, Amer. Geol., Vol. 19, 1897, pp. 267–270.

TOPOGRAPHIC MAPS

Crater Lakes

Lassen Peak, Cal.	Ashland, Oreg.	Crater Lake Special

Delta and Coastal Plain Lakes

Point à la Hache, La.	Norfolk Special	Salton Sink, Cal.

Glacial Lake Plains

Casselton, N.D.	Fargo, N.D.	Tower, N.D.

Finger Lakes

Watkins, N.Y.	Skaneateles, N.Y.	Ovid, N.Y

See also maps showing forms below, as well as above, lake level in Birge and Juday's paper, Bull. U. S. Bureau of Fisheries, Vol. 32, 1912, Washington, 1914.

Glacial Lakes and Swamps

Becket, Mass.	Monadnock, N.H.	Ashby, Minn.
Mt. Lyell, Cal.	Minneapolis, Minn.	Madison, Wis.
Oconomowoc, Wis.	Newcomb, N.Y.	Ann Arbor, Mich.

Hydrographic maps of 12 Wisconsin lakes, by L. S. Smith, Wis. Geol. Survey; see also the 29 maps in Juday's Bull. 27, Wis. Geol. Survey, 1914.

Great Lakes

Charts of the whole lake, of parts, and of harbours, for example: Lake Superior, S., Sf., Sf.8, etc., and similar charts of the other Great Lakes — Survey of the Northern and Northwestern Lakes, U. S. War Dept., Detroit, Mich., or Buffalo, N.Y.

Ox-bow Lakes

Miss. R. Commission Charts, 1 : 20,000, Nos. 23, 24, 52, 55, etc.

Butler, Mo.	Junction City, Kan.	Elk Pt., S.D.
St. Louis, Mo.	Marshall, Mo.	Millikin, La.

Alkali Flats and Playas

Sierraville, Cal.	Van Horn, Tex.	Disaster, Nev.

Coastal Plain Swamps

Glassboro, N.J.	Hempstead, N.Y.	Norfolk Special

Delta Swamps

Donaldsonville, La.	Point à la Hache, La.

Lake Swamps

Pulaski, N.Y.	Plattsburg, N.Y.	Oswego, N.Y.

River Swamps

Glassboro, N.J.	Marysville, Cal.	Minneapolis, Minn.

Salt Marshes

San Francisco, Cal.	New London, Conn.	Norfolk Special
New Haven, Conn.	Atlantic City, N.J.	Stonington, Conn.
Brooklyn, N.Y.	Boston Bay, Mass.	New York City and Vicinity

CHAPTER XI

SHORELINES

Factors Involved

The Ever Changing Coast. — The contact between the sea and the land, and to a lesser degree between lake water and land, is a zone of active change, and, as a result of such change, topographic forms of great diversity have been caused. The nature of the larger elements of a coast is dependent upon the factors discussed below.

Rock Structure and Attitude. — Along the coast, as on the land back from the coast, there is great variety among the rocks, from the standpoint both of position and condition; and, as these are attacked by agents of denudation, the resulting topographic form of the coast varies with the nature of the coast line rock.

Crustal Movements. — Crustal movements are readily noticeable along the sea coast, for the sea level is a delicate register of even slight change. These movements consist of (*a*) elevation, (*b*) depression, (*c*) mountain growth.

Activity of Agents of Land Denudation. — The agents of denudation on the land — weathering, wind, rain wash, rivers, and glaciers — affect the coast line, either by erosion, or by deposition, or by both combined.

Activity of Organisms. — In the ocean itself there are organisms, both plant and animal, which either aid or retard erosion, and which, by their abundant growth, aid in coast line deposit.

Erosive Agents of the Sea. — There are also movements of the water which work effectively in erosion, transportation, and deposition. These movements are (*a*) waves, (*b*) tides, (*c*) currents, the waves being far the most important. By the waves the land contact is being incessantly attacked, and a large part of the detail of shore form is the result of this attack, either by a direct cutting or by deposit of the rock fragments removed. But it is not wave work alone, for all the other factors mentioned above are in operation, and the coast form is the outcome of the complex interaction and interrelation of a number of these. The nature of this complexity of processes, activities, and conditions will appear as the subject is developed.

Effect of Submergence

Relation to Topography. — Either a lowering of the land, or a rise of the water level, drowns a portion of the land. The new coast line will be a horizontal line, traced at the contact of sea and land. If the land is perfectly level, this line will be straight; but if the land surface is irregular, the new coast line will be sinuous; and, since most land has been subjected to denudation, a sinuous coast line will ordinarily result from depression. The degree of sinuosity will vary with the degree of dissection of the sunken land; but, in all cases, the water will extend up valleys, forming bays or harbours, while divides between valleys will project, forming points, capes, or peninsulas. Hills completely submerged will form shoals, and hills partly submerged may be entirely surrounded by water, forming islands, separated from other islands or from the mainland by straits.

The Submergence of Rugged Land. — If the sunken land is rugged, the bays will be long, the promontories high, the coast line bold and irregular, and the depths of the water over the sunken land extremely variable. Since rugged lands are commonly underlaid by consolidated rock, the coast line will, in all probability, consist of resistant rock, perhaps varying greatly in kind and position from place to place.

The Submergence of Plains. — If the sunken land is a plain, or only gently undulating, the bays will be small, the promontories low, the water off shore shallow, and the variations in depths only moderate in amount. Such a coast line may be fairly regular, or it may be very irregular, according to the topography of the sunken land; but it cannot be a bold coast. Whether it is also a rock coast, or is one of unconsolidated material, will depend upon the nature of the submerged land; but unconsolidated strata form a great majority of such coast lines in the world.

Coast of Norway. — Northwestern Europe and northeastern North America have a coast line whose major features seem to be due to sinking of the land. In Europe the Scandinavian peninsula is the higher part of a mountainous land, partly submerged. Off the western coast are many shoals, on which food fish live in great abundance, so that the fishing banks are an important source of food. The coast itself is exceedingly irregular, with a maze of rocky islands, mountain-walled fiords, and passageways between the islands and the mainland. It is one of the grand scenic spots of the world, and each summer the coast of Norway is visited by a stream of tourists. For centuries it has been the home of hardy mariners, trained to a sea-faring life by the forbidding nature of the land itself, by the invitation offered by the quiet waters of the fiords and sounds, and by the supply of food which the water contains.

Coast of Scotland. — A similar coast is found in Scotland, but submerged valleys separate the British Isles from one another and from the mainland. The North Sea and the Baltic Sea are shallow bodies of water, spread over a submerged plain, a part of which rises above the sea in southern England and along the coast of the mainland of Europe. Here the coast is much less irregular, and far less bold; in fact, for much of the distance it rises almost imperceptibly out of the sea, and shallow water extends far off shore. The river mouths are broad bays or estuaries, with low-lying shores, contrasting strikingly with the rugged, irregular, rock-bound coast of Scotland and Norway. Where the level of the plain was higher, as in Denmark, low islands and peninsulas rise above the sea. The coast of the low, hilly land of Sweden and Finland is intermediate in form between that of the level plain and the rugged mountainous land. Here are found a maze of small rock islands and promontories, and partly enclosed bodies of water; but, in spite of the irregularity, the relief is slight.

Northeast Coast of North America. — Eastern North America illustrates the same condition. Labrador, Nova Scotia, Hudson Bay, Gulf of St. Lawrence, Newfoundland, the Grand Banks of Newfoundland, and the islands of the Arctic are all the result of the subsidence of an irregular mountainous land. The coast is prevailingly rock-bound, it is notably irregular both in general features and in detail, with a multitude of fiords, bays, straits, islands, and promontories, and it is, on the whole, a rugged and bold coast.

Coast South of New York. — South of New York the coast is still irregular, for the latest movement has been downward; but here the land is a plain. Throughout, this coast is of unconsolidated strata, and the river mouths are all drowned, so that the tide enters into them and in places transforms them to estuaries or bays. These arms of the sea increase in breadth and depth toward the north, partly because the land surface was more irregular there, and partly because subsidence was greater. Accordingly, there are numerous, broad, shallow bays, with low-lying coast, such as Delaware Bay, Chesapeake Bay and its branches, Mobile Bay, and Galveston Bay.

Between the partly drowned southern plains and the sunken mountainous lands of the north is an intermediate area of low, hilly land, also partly drowned, resembling somewhat closely the coast of Sweden. Thus from New York to New Brunswick there is a low, prevailingly rock-bound coast, with a multitude of islands, promontories, bays, harbours, and straits (Pl. X).

Other Submerged Coasts. — Similar drowned coasts are found in other parts of the world: in northwestern United States, on the Dinaric coast of the eastern shore of the Adriatic, and in many other places. Drowned coasts are also common in lakes, whose waters are often forced to rise over an irregular land whose topography was developed before the lake came into existence. The eastern end of Lake Ontario at the Thousand Islands, and the islands of Georgian Bay in Lake Huron, are illustrations; and the bays along the south shore of Lake Ontario and other of the Great Lakes are also instances of the drowning of land by the rise of lake-water. Many irregular lakes, such as abound in Maine, Canada, Finland, and Sweden, owe their irregular shoreline to the fact that the lake waters are spread over an irregular land surface.

Effect of Elevation

Relation to Sea Bottom. — Uplift brings the sea bottom into the air; and the coast line has a form dependent upon the outline of the sea bottom. This outline may be irregular, as it would be, for example, if there should be an uplift along the northeastern coast of New England; but more commonly it would be regular, for the deposit of sediment in the sea tends to level the bottom. Thus in time the sea bottom off New England, whose irregular form is due to the fact that it is a recently submerged, hilly land, will become smoothed over by sediment deposit. Because of sediment deposit the greater portion of the ocean floor is a plain; and it is, moreover, made of unconsolidated rock.

By the uplift of such a sea bottom a straight coast line is established, and the land rises gently out of the sea, while shallow water exists off the coast. At the coast line itself the waves come in contact with unconsolidated sediments, and these also lie off shore on the shallow sea bottom, and form the land back of the coast. Such a coast is difficult to approach because of the shoal water, and there are few harbours in which a vessel can anchor, though there may be some indentations where there were depressions in the sea bottom.

Illustrations from North and South America. — From New York southward to Central America there is such an uplifted sea bottom, though subsequent to its uplift there has been slight subsidence, as noted above. In general, therefore, it fits the case fairly well, though there are more irregularities than normal, because of later, slight sinking, especially toward the north. On the whole, the coast is straight, the sea is shallow off shore, there are few good harbours, and the sea bottom, the land, and the shore line are all unconsolidated rock. The peninsulas of Florida and Yucatan are higher portions of the sea floor, the cause for which is not certainly known. A similar uplifted coast is found in eastern Argentina, and there are strips of upraised sea bottom, forming narrow coastal plains with straight shorelines, along the coast of Africa and other continents. Very often such uplifted coasts are only local and connected with mountain growth.

Effect of Mountain Growth

Uplifted Mountain Coasts. — Mountain uplift, either by folding, or by faulting, sometimes occurs along the sea coast, as in western South America. This gives rise to a fairly regular coast line, with few harbours, capes, and peninsulas (Pl. VI). Back of the coast the mountains rise steeply, and the sea bottom slopes rapidly away from the continent. Thus, west of South America the sea bottom lies 15,000 to 20,000 feet below sea level a short distance off shore; and in a distance of 75 miles there is a difference in elevation of 40,000 feet between the sea bottom and the lofty Andean peaks. The coast ranges of western United States give rise to a similar, though less regular, coast line. During the mountain uplift, narrow strips of sea bottom have been raised, so that there is often a belt of coastal plain between the mountains and the sea, but the coast is essentially a straight mountain coast. Because of the few harbours, the narrow strip of level land, and the lofty mountains, cutting off communication farther inland, such a coast is not suited to dense population and high development of industries.

Mountain Ranges in the Sea. — Elsewhere mountain ranges rise out of the sea, their crests forming chains of islands, such as the West Indies, the East Indies, New Zealand, and the Japanese and Philippine Islands. Such islands are usually elongated in the direction of the mountain chain; but volcanic eruption often gives rise to roughly circular islands in such mountain chains; and sometimes the volcanic peaks are the only portions of the mountain chain that rise above the sea. This is especially true of mountains rising above the floor of the deep ocean far from land, as in the Hawaiian Islands, and many others in the open Pacific and Indian oceans.

Seas between Continents and Off-lying Islands. — When mountains rise off the mainland coast the island chains to which they give rise often partly enclose arms of the sea, such as the Caribbean Sea, the Gulf of Mexico, Japan Sea, and China Sea. And since mountain uplift is usually, if not always, accompanied by neighbouring sinking of the land, the beds of such enclosed seas are often very deep as a result of subsidence.

Mountain Peninsulas. — Mountains often extend as spurs from the mainland out into the sea, thus forming peninsulas, as do the Coast Ranges in lower California, the Alaskan Range in the Alaska Peninsula, the Atlas Mountains in Tunis, the Apennines (Fig. 225), and the Balkan Mountains in the Balkan Peninsula. Bays, such as the Gulf of California, the Adriatic Sea, and others are formed in this way, often owing a part of their depth, however, to subsidence.

Plateau Peninsulas. — Great crustal movements, such as plateau and mountain uplift, give rise to large peninsulas, and subsidence forms great seas and gulfs. In such ways were formed the peninsulas of Indo-China, India, Arabia, and Spain, with their associated seas and gulfs.

Mediterranean Seas. — The Mediterranean occupies a sunken portion of the earth's crust between the mountains of Europe and Africa. The Caribbean Sea and Gulf of Mexico are of similar origin. The bed of the Mediterranean Sea of Europe and Africa lies over 14,000 feet below the level of the sea in places. It is almost divided in two where the mountains of Italy and of northern Africa approach each other, and are connected by a submarine ridge. The mountains almost come together again at the Straits of Gibraltar. Its coast is very irregular, owing to the projection of mountainous peninsulas, and mountainous islands and volcanic peaks rise above its surface.

FIG. 225. — The precipitous coast of Italy near Amalfi, with roads, houses, and a town built under difficulties.

Some of the islands and mountainous coasts are parts of the earth's crust that have not sunk below sea level, others are raised by mountain uplift. Along the coast of Italy are strips of coastal plain, with straight coast line uplifted above the sea; and in Greece, and on the eastern shore of the Adriatic, there are drowned coasts, where sinking of the land has admitted the sea into the mountainous valleys. Here, as in other mountain regions, the adjustment of the earth's crust is not complete, and subsidence and uplift are still in progress in places.

Complexity of Crustal Movements

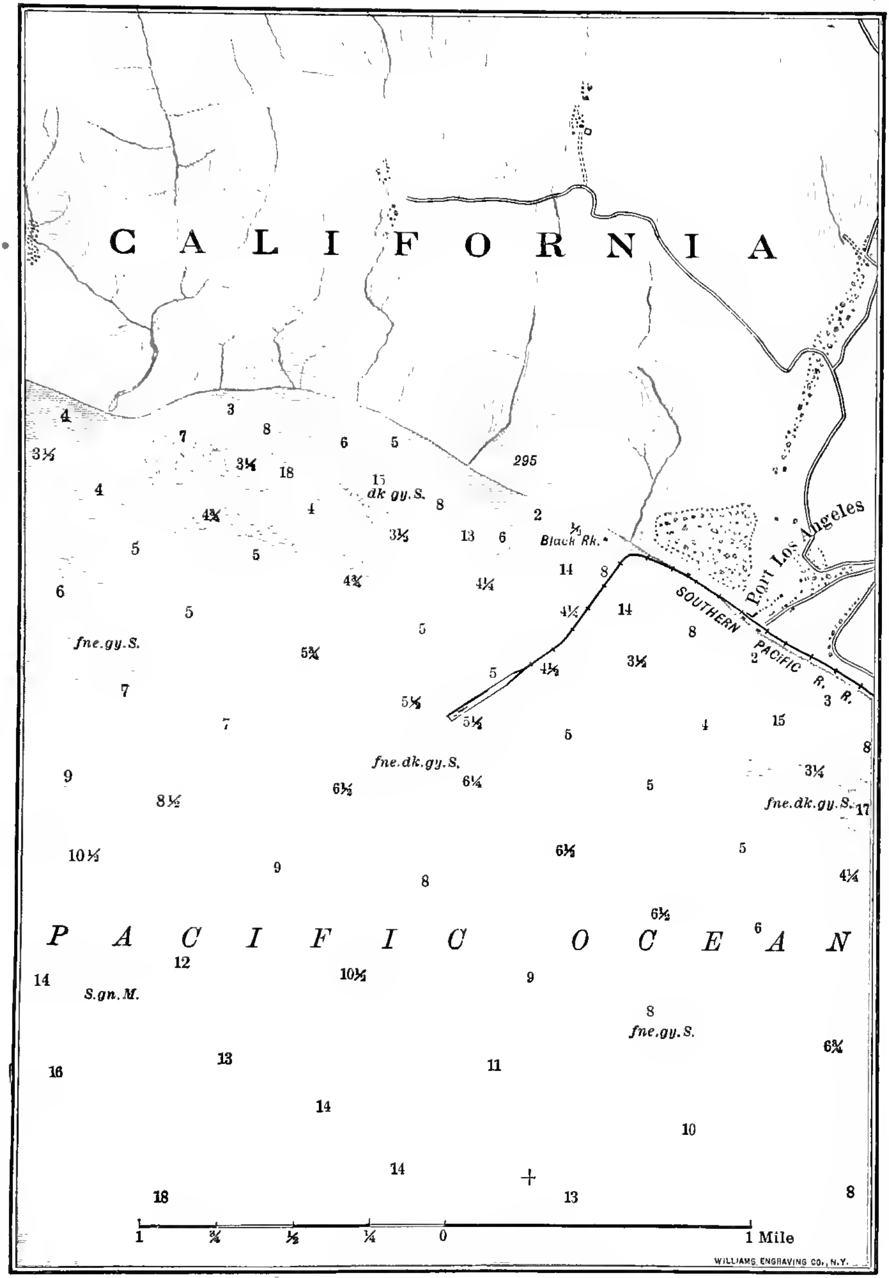
Simple Coasts Rare. — In some coasts the recent changes, by which the present coast line has been determined, have been rather simple. Such is the case, for example, along the mountain coast of western America, and in the sunken coasts of northwestern Europe and northeastern North America. But even in such cases there are evidences of more than one movement. For example, in western America, while the main movement has been upward, there has been recent down sinking at the northern and southern ends and still more local subsidence in places, as at San Francisco Bay. The sunken coast of northwestern Europe and northeastern America has risen somewhat since its greatest subsidence, and beaches, wave-cut cliffs, and marine clays are found on the land, well above sea level. It has already been stated that the uplift of the coastal plain of southern United States was followed by a slight subsidence.

Complex History the Rule. — Some coasts have had an exceedingly complex history, and there are notable differences from place to place. This is well illustrated in the Mediterranean, where there are straight mountain coasts, irregular mountain coasts due to uplift, irregular, drowned mountain coasts, uplifted coastal plains, volcanic coasts, and coasts where uplift and subsidence have succeeded one another.

Present Coast Lines Unstable. — Whether the sea coast of any considerable part of the earth has ever stood for long periods at one level in relation to the sea cannot be stated; but at present the coast line is one of great instability, having risen or been depressed, or both, within very recent periods; and many coast lines are known, even now, to be rising or sinking. Ever so slight a change of level swings the zone of wave work up or down, and only a moderate change is necessary to completely alter the form and condition of the sea coast.

The Effect of Land Agents of Erosion

Effect of Weathering. — Weathering operates upon the sea coast, as it does on all other exposed land surfaces, and is an effective aid to wave work in supplying rock fragments, for use as tools and for deposit in the sea. Three factors tend to make weathering active along the shoreline strip. (1) There is much steep rock slope, where wave



COAST OF CALIFORNIA

Map to show the harbor of Los Angeles, wave-cut cliffs, sandy deposits near shore (brown stipple), kelp at greater depths (blue pattern), and sand or mud in various depths of water. Contour interval 20 feet. Elevations on the land in feet; depths within brown stipple in feet; other depths in fathoms. (After chart of Santa Monica Bay, No. 5144, United States Coast and Geodetic Survey.)

attack is active. (2) Vegetation cover is absent or sparse on many rock coasts to which the salt spray reaches. (3) The rocks are frequently wet, thus aiding rock disintegration, and the salt water is more favourable to mineral change than rain water, owing to its chemical composition. But neither weathering nor rain wash give rise to any notable shore forms, or changes different from those of the land back of the shore.

Effect of Wind Work. — The work of the wind along coasts has already been discussed (pp. 59–64), and will need no further consideration than incidental mention in connection with the coastal forms upon which it is especially active. It may perhaps be stated that the wind drives sediment into the sea, and that, upon desert coasts, this may be a very important aid in the supply of sediment to the waves and currents.

Effect of Rivers. — Rivers contribute far more sediment than the wind does, and at times much more than the waves and currents can dispose of. This is one of the reasons for the presence of sand bars along some coasts, and it has already been shown that it is the explanation of deltas at river mouths. Where waves and currents are least effective, as in lakes and bays, delta deposits are most common. In bays, as in lakes, the tendency of the inflowing streams is to fill them with sediment, both by the growth of deltas and by the deposit of sediment upon the bottom of the bays. Many coasts have been partly straightened by the filling of bays, and many others have alluvial flats at the bay heads or bay margins.

Illustrations from Italy, California, and Elsewhere. — This is true in Italy, for example, where the Po has filled a broad valley, and the river sediment forms a plain along the Adriatic coast far to the south. In Greece the heads of many bays are alluvial flats, and there are similar river-filled bays and bay heads in Asia Minor, the Persian Gulf, western United States, and many other places. An excellent illustration of this is at the mouth of the Colorado River at the head of the Gulf of California. Here the head of the gulf is a broad alluvial flat, really the Colorado delta, bordered by mountains. The growth of this delta has cut off the upper part of the gulf, leaving a basin whose bed is 300 feet below sea level at the lowest point. The climate is so arid that this basin is not filled with water, though a shallow lake, Salton Sea, now occupies a small part of it. Now and then, as in 1905, the Colorado sends some of its water down into this basin, causing Salton Sea to rise and doing much damage to the irrigated lands in this low-lying area.

Estuaries and Allied Forms. — Rivers affect coast lines also by the formation of valleys, into which the ocean water may enter when there is subsidence of the land, forming bays, estuaries, and harbours. Even the river mouth itself, without subsidence, may make a harbour, for the river water scours out a channel slightly below sea level. Some of the larger rivers are navigable by ocean-going vessels, as the Mississippi is as far as New Orleans, 100 miles from the river mouth. The mouths of smaller streams are apt to be too shallow, or are too much obstructed by sand bars for use as harbours, unless, by subsidence, a broader opening is made.

Fiords Mainly Produced by Glacial Erosion. — It is only recently that it has become generally recognized that glaciers have had a truly

FIG. 226. — A fiord on the coast of Norway.

important share in the shaping of some coast lines. Glaciers are able to erode their beds even well below sea level, for their ends will not float until a depth of 600 to 800 feet is reached in an ice front 100 feet high, and 1200 to 1400 feet in the case of the much commoner glacier terminus, which is 200 feet or more in height. Thus erosive power can extend that far at least. Back from the glacier terminus it may extend even lower, for glaciers do not need an even grade for their beds, but are capable of eroding basins so long as an adequate surface grade is maintained. The evidence is now deemed by most glacialists to be conclusive that glaciers cut deeply into their beds, lowering them 1000 feet, 1500 feet, or even more in favourable situations.

Among the places where there is clearest evidence of such erosion are the fiorded coasts, as Norway (Fig. 226), Greenland, Alaska, British Columbia, Patagonia, and New Zealand. Here the evidence indicates that valleys whose beds were above sea level before the Glacial Period were eroded below sea level by glacial sculpture alone, during the ice occupation. When the ice disappeared, the sea flooded the valleys and the fiord coast came into existence. In Alaska it has been shown that submerged hanging valleys are common (Fig. 227). Fiords (Pl. V), with their deep waters, steeply rising walls, and hanging valleys above and below sea level do not require for their explanation anything

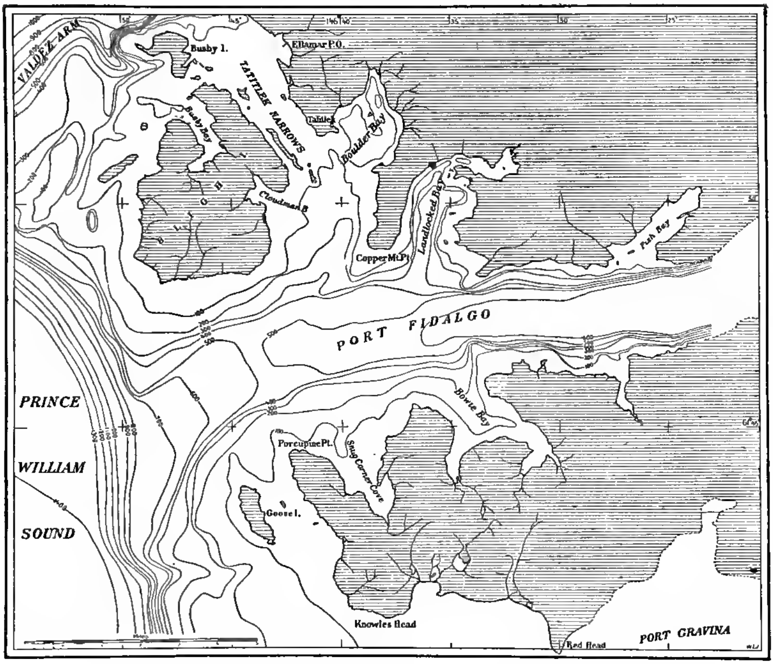


FIG. 227. — An Alaskan fiord and submerged hanging valleys.

further than this, — though in some cases there is independent evidence that there has been slight subsidence in addition. The fiord characteristics are mainly the result of glacial erosion, and the subsidence, if present, has been merely an incident of secondary importance.

THE AGENTS OF EROSION ALONG COASTS

Waves, tides, and currents, singly or combined, are ceaselessly at work along the margin of the land, modifying the coast line. The sea coast, especially that exposed to the vigorous waves of the open ocean, is the seat of some of the most active changes on the earth. Coast lines are worn back, or built forward, as the case may be, at so rapid a rate that their effects became noticeable in some cases in the course of only a few years, while during the centuries of historic time striking alterations in the coast line have taken place.

Wind Waves. — Of the oceanic agencies the wind waves are by far the most important. They are generated by the friction of the moving air upon the mobile water surface, as we may easily illustrate by blowing upon a basin of water. With steady strong winds blowing over a great expanse of water, waves of large dimensions may be generated. The discussion of the nature of wind waves, and the production of ground swell, white caps, and wind drift currents, is, for the present, postponed (see Chap. XXI).

Breakers, Surf, and Alongshore Currents. — In the open ocean wind waves are important to navigation, being a source of danger

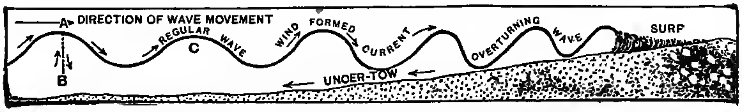


FIG. 228. — Diagram of a wave approaching shore and forming surf, through interference of the bottom with the motion of the water particles. (See Fig. 412.)

to small or weak craft; but the ocean is so deep that they produce no effect upon the solid earth. As they approach the land, however, all this is changed, and even the condition of the wave is altered. Near the coast, the motion of the particles of water (Fig. 228) is interfered

FIG. 229. — Powerful waves breaking on the coast of New England.

with by friction along the bottom, the wave becomes steep-sided toward the land, and finally topples over, and a huge volume of water rushes with resistless force up on the shore. Such a wave is a *breaker*, and a succession of them forms *surf*. When waves break diagonally on a coast, they set up a movement of the water known as the *alongshore current*.

Wave Erosion. — The breakers exert enormous force as they strike blow after blow against the coast (Fig. 229). Thus it is recorded that a 300 pound bell, 100 feet above high water mark, was wrenched off by the waves on the west coast of England. Breakwaters are torn to pieces, and stones ten to fifty tons in weight are moved about by the waves. In its powerful action the breaker works (1) by

Fig. 230. — Beach of fine sand at Atlantic City, N.J., with very moderate surf.

its mechanical force as it rushes along, (2) by alternate compression and expansion of air in crevices in the rock, (3) by hydraulic pressure as the water is driven into the crevices, (4) by hurling rock against rock, that is, by using rock fragments as tools.

It is by such attack, repeated at intervals of a few minutes, sometimes with great violence, sometimes with less vigour, but rarely quiet for any length of time, that exposed coasts, even though made of the hardest of rocks, are being worn away at rapid rate. In this attack the rate varies (*a*) with the exposure, (*b*) with the kind of rock. Weak rocks, or rocks with abundant joint planes, fall ready prey to the waves, but none are exempt. Combined with the mechanical work of the waves is some chemical action and weathering; and modifying the rate of work is the influence of animal and plant life, and, on some coasts, of ice.

Disposal of Wave-eroded Material. — The materials obtained by the waves, or turned over to them from the land, must be disposed of, or else the débris will accumulate. There are six processes by which the materials are disposed of. (1) Some is dissolved by the sea water and therefore removed in solution. (2) Much is ground up by the constant beating of the waves, and thus reduced to such fine form that it is readily removed in suspension (Fig. 230). (3) A very large portion, both large and small fragments, is driven along the coast by the diagonal approach of the waves. A wave that strikes the coast at exact right angles to its course will rise and fall without any lateral component; but, owing to the irregularity of the coast and to the fact that waves will only occasionally approach exactly normal to the coast, the waves commonly strike the coast diagonally, and there is thus a tendency to push rock fragments along the coast in one direction or the other, according to the direction from which the waves most frequently come. (4) There is a similar tendency for the smaller fragments to drift along the coast in the wind drift current, which, upon reaching the coast, is deflected along it. (5) An outward movement of water along the bottom, the *undertow* (Fig. 228), occurs along wave-beaten coasts, and, in this, rock fragments, especially those of small size, are moved away from the coast. (6) Tidal and other currents remove fine-grained rock fragments.

The Tidal Currents

Twice each day the ocean surface, in most places, rises and falls, as a result of the tidal wave which the pull of sun and moon generates in the hydrosphere (Chap. XXI). Throughout most of the ocean the movement is unnoticeable, and, even on most coasts, it is a factor of slight importance in modifying the shore current, as when it passes through narrow straits, or is otherwise influenced by irregularities of the coast line or of the sea bottom.

Ordinarily the tidal currents move so slowly that they can do no more than transport the finest sediment, but locally they attain sufficient velocity to move sand. Along some narrow channels, they are effective agents, not merely of transportation, but of scouring as well. It is, however, in transportation and deposition that the tidal currents are most effective in modifying the shorelines.

Ocean Currents

In addition to the wind drift and tidal currents, there are larger movements of ocean water, flowing with a fair degree of permanency. Ocean currents are important in modifying temperature, and in influencing the distribution and abundance of marine organisms; but excepting as they encourage the work of organisms they are only of minor importance in shoreline development. Undoubtedly they aid in the distribution of sediment; but, if they scour at all, it is only locally and mainly on the bottom offshore.

Work of Erosive Agents

Upon all coasts the agents of erosion are at work, with a vigour that varies from place to place, and with a result that is also widely variable, according to conditions. Whether the initial form be that of a drowned coast, or a mountain coast, or an uplifted sea bottom, the waves and currents are active, and change is in progress. Roughly we may divide the result of this activity into two categories, (1) destructional work, (2) constructional work; but it must be borne in mind that the two grade into one another, and overlap.

Destructional Work

Formation of Sea Cliffs. — In destructional work the waves are the main agents. The zone of most vigorous wave attack extends through but a few feet vertically, and along this narrow horizontal zone the

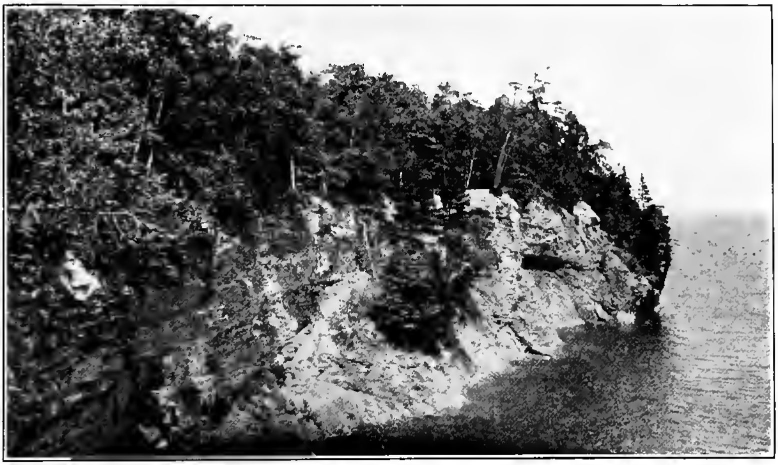


Fig. 231. — Wave-cut cliff on Lake Superior, near Marquette, Mich.

rock is planed away. The tendency is to undercut the coast along this horizontal plane, and in some cases this is actually accomplished; but by weathering, by the fall of rock under the pull of gravity, and by the attack of waves at levels above the zone of greatest activity, there is usually such active removal of the rock, that the overhanging condition is not common. The result is a precipitous sea cliff (Fig. 231). It may be 600 to 1000 feet high, though sea cliffs over one or two hundred feet high are not common. It is sometimes vertical, or over-

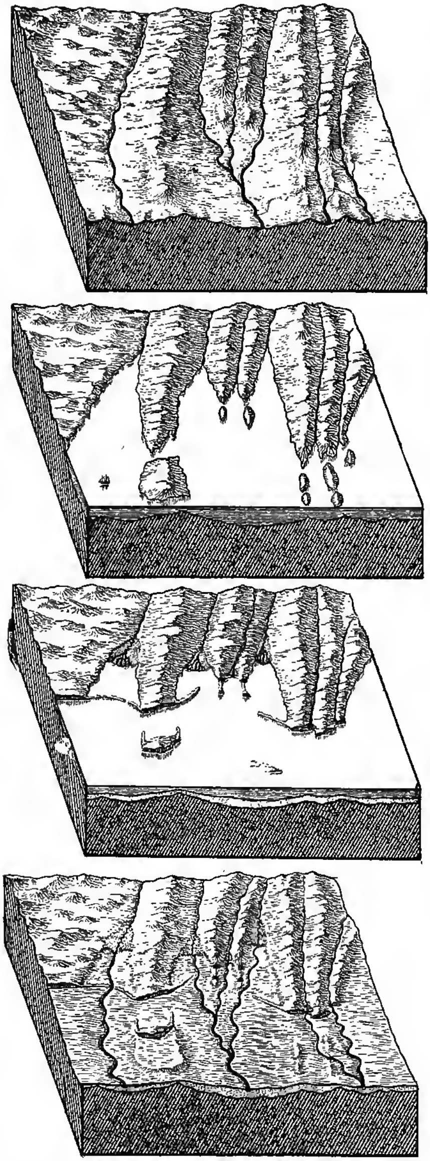


FIG. 232.—Block diagrams to show (1) a mountainous region of resistant rock; (2) the bays, peninsulas, and islands resulting from sinking of the land; (3) the cliffs and spits resulting from wave work; (4) the features revealed by subsequent elevation. For the life history of a coast in weak rock see Fig. 246.

hanging, but usually some degrees less than vertical. The angle of slope varies with the rock and the vigour of the waves, being steepest in resistant massive rocks, and where the waves are most active.

In unconsolidated strata the sea cliff commonly remains approximately at the angle of rest of unconsolidated material, from 30° to 35°, and there is little vegetation, since there is frequent sliding of the cliff face as the waves move material from its base. A similar slope may be maintained in consolidated rock where the wave attack is slow, or where the rock is much jointed, and, therefore, easily weathered away. Such sea cliffs are characteristic features of headlands or other exposed parts of the coast, but they can be present only where the waves are able to remove the material that comes to them. If they fail in this, they then cease their attack on the cliff and it wastes away.

The rate of recession of sea cliffs in unconsolidated strata is indicated by Shaler's computation that the Nashaquitsa Cliffs on Martha's Vineyard Island receded 220 feet from 1846 to 1886, or about $5\frac{1}{2}$ feet a year, and by Roorbach's studies of drumlins in Boston harbour, where a cliff retreated 9 inches a year from 1860 to 1908. On the coast of England the average annual rate is said to be from 9 to 20 times this latter amount.

Where the waves have planed far back into the land, or where they are attacking a highland coast, the cliff is high; on the other extreme, where the relief of the land is low, or the extent of cutting has been slight, the sea cliff may be but a few feet in height. The irregularity of the cliff is caused by (1) irregularities in the land (Fig. 232), (2) variations in wave force, (3) differences in character of the rock (Fig. 246), (4) the effect of weathering.

Much depends upon the nature of the rock. If it is massive, the cliff approaches greatest regularity, but if it is jointed, or varies in resistance, due to stratification or other causes, the cliff may become quite irregular, and the irregularities vary according to the inclination of the layers as well as to their resistance. A sea cliff in horizontal strata has a notably different form from one in vertical strata; there is a different form produced when the strata dip toward the sea than that in strata dipping toward the land; and the degree of inclination adds further cause for variation in cliff form. An analysis of sea cliff form, therefore, would need to include a complex series of factors. A majority of sea cliffs are sloping rather than vertical or overhanging, from which it may be inferred that wave attack is less effective than the work of subaërial agents, though the relationships of joints, of bedding, and of the influence of gravity must needs be considered in connection with each individual cliff.

Spouting Horns or Blow Holes. — Among the irregularities are some sufficiently characteristic and common to be given names. One of these is the *spouting horn*, or *blow hole*, a place where, when the waves break, either air or water is forced out of a cavity in the rock, perhaps at some distance from the place where the wave is breaking. It is due to the presence of an opening, often along a joint plane, into which the wave enters, forcing air or water out of the other end of the cavity either by compressing air in the cavity or by passing through it. Sometimes the water spouts, fountain-like, with the incoming of each large wave; at other times the air is alternately sucked in or forced out as the wave recedes or advances.

Sea Caves. — Where the rock varies in resistance, or the direction of wave attack favours, the cliffs are locally undercut, forming pockets or arches, called *sea caves* (Figs. 233, 234). Once these are started, the swirling wave may tend to enlarge them, much as the falling water of rivers gives rise to pot holes. Recession may even proceed so far as to develop natural bridges beneath which the waves rush. Sea caves may develop in any rock, but they are most common in limestone, doubtless partly because of its softness and solubility in the ocean water, but very often as a result of the discovery by the waves of subterraneous caverns, previously developed by land drainage.

Chasms. — Vertical weakness in the rock leads to the excavation of *chasms,* or narrow indentations. These may be due to the presence of a soft, or soluble, or jointed layer. They occur most commonly in vertical sedimentary layers, or along narrow dikes of igneous rock. When the indentation is begun, the wave attack increases in vigour, because of the increased intensity of the breaking wave when thus directed. This leads to a rapid extension of the chasm; but this

FIG. 233. — Sea cave of elevated shoreline on coast of California. (Arnold, U. S. Geol. Survey.)

extension is limited, for soon such a length is reached that the wave wears itself out by friction against the sides and bottom. Then the headward extension of the chasm must await either the cutting back of the headland, at the chasm mouth, or the widening of the chasm mouth so as to admit a greater volume of water. The latter action may result in the production of a small bay or cove.

Large bays cannot result from wave work, for if there is, for any reason, a concentration of wave activity on a part of the coast, or if there is an area of weak rock, the indentation that would naturally result soon becomes a place where the waves lose force by friction. After a certain size is reached, there comes a balance in which the slackened wave attack at the bay head no longer exceeds the rate of attack at the headland. Thus a cliffed coast line is commonly sinuous, with shallow indentations and slightly projecting headlands;

but if there are large bays, or harbours, we may be certain that they are due to other causes than wave erosion.

Stacks. — As the coast wears back, certain parts, especially at the headlands, are temporarily left unconsumed, forming small rock

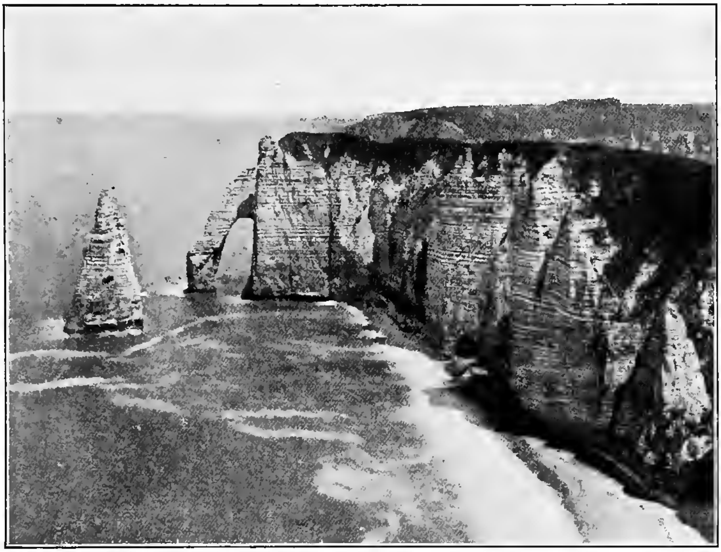


FIG. 234. — A stack and a wave-cut arch in a sea cliff on the coast of France.

islands, or *stacks*, or *skerries*, often conspicuous and striking features of the coast, and sometimes pierced by sea caves, or partly divided by chasms. Such remnants of the worn-back coast may be due to some peculiarity of the rock, or to some deflection of the wave attack; but their duration cannot ordinarily be long in the face of the oceanic forces operating round about them (Fig. 234).

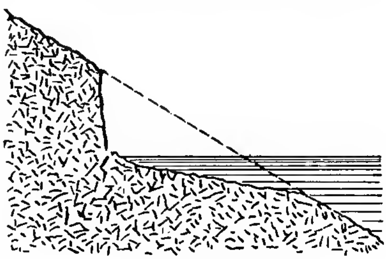


FIG. 235. — A sea cliff and rock bench. (Gilbert.)

Offshore Benches. — As the waves plane back the coast line, they leave a shallow *offshore bench* or shelf (Fig. 235). Slowly the water becomes deeper on the offshore bench, for the waves and currents gradually wear the rock away; if they did not, the bench would in time become so broad an area of shallow water that the waves would wear themselves out in passing over it, and reach the shore without power to further cut the sea cliff back. Even when the average depth of water on the offshore bench has become deep enough so that the waves do not break in passing over it, there may be a shoal near, and hidden reefs, not yet consumed.

Dangers to Navigation. — Because of the offshore bench, approach to a cliffed coast is dangerous for vessels, and many a wreck has occurred upon it. Very often the disaster has been complete, for the storm waves in such a place are commonly high, owing to the influence of the shallow water. The vessel receives the full force of the breakers, launching small boats is difficult or impossible, and the cliff-bound shore offers no safe haven for them, even if they are successfully launched.

Constructive Work

Formation of Beaches. — A sea cliff base is commonly strewn with rock fragments, wrenched loose by the waves, or fallen from the cliff (Fig. 236). These are used by the waves as tools for further attack against the land, and, as they are washed about, they are ground down and the fragments either carried offshore or driven along the coast. In places of especially active supply, or in indentations where wave force is diminished, these fragments may accumulate, forming *beaches*. The accumulation in the indentation is encouraged by the driving of fragments along the coast by the diagonal wash of the waves.

The material in the beach varies with the source of supply, both in kind of work, and in size of fragment. Upon surf-beaten coasts the beach may be of boulders or of large cobblestones; where the supply is extensive, even on exposed coasts, the beach may be of pebbles; or it may be of sand. Even with moderate supply, sand and pebble beaches commonly develop in indentations or in other situations where the waves are not of great size.

Pocket Beaches and Crescent Beaches. — Along rock-bound coasts, beaches of boulders or pebbles are commonly formed at the head of minor indentations, into which they have been driven by the waves. Small patches of this nature are called *pocket beaches*, and large ones often form *crescent beaches*. Such beaches are really mills, in which the rock fragments are ground down to such a state of fineness as to permit their removal from the pocket in which they have become lodged. As the surf rolls up and down on the beach, the pebbles, cobbles, and even boulders are rolled back and forth, soon assuming a rounded form, and rapidly diminishing in size. Were it not for this, the indentations would become filled with fragments wrested from the headlands, and then the headlands themselves would be littered by a protective sheet of rock fragments, thus putting an effective check upon the recession of the shoreline.

The crescentic form of beaches is characteristic of indentations, for it is the result of a tendency toward equilibrium between supply and removal. If waves of a given average velocity enter the indentation

FIG. 236. — Beach gravels at base of sea cliff, Hinchinbrook Island, Alaska. (White.)

with a straight crest, they begin to bend, owing to the less rapid motion along the margins of the indentations where retarded by friction, and they reach the head of the indentation with greater vigour in the centre than on the sides. As a result, the beach deposit has a similar curved, or crescentic form. The size of the crescent depends upon the size of the indentation; the extent to which the curve develops depends upon (*a*) the force of the waves, (*b*) the depth of water in the indentation, (*c*) the amount of material supplied to the beach. When in perfect equilibrium, a wave from the open ocean will break upon all parts of the crescent beach at the same instant.

Movement of Material Along Shore. — On a very irregular coast, such as a drowned coast, the exposed headlands are commonly cliffed by wave attack; but the indentations are in many cases, and perhaps in most, quite free from the attack of the open ocean waves, though modified to some extent by waves that develop within their own confines. The rock fragments wrested from the headlands are in part driven along the coast by waves and alongshore currents, and, coming to the opening of the indentation, are driven into it. How far in they may be driven, will depend upon (1) the size of the fragments, (2) the abundance of the material, (3) the force of the waves,

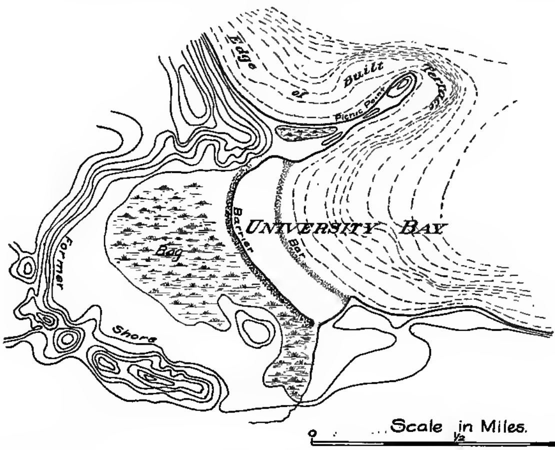


FIG. 237. — Head of a bay in Lake Mendota closed by a barrier bar and converted into a bog. A second bar has subsequently been built up part way to lake level. (Wisconsin Geological Survey.)

(4) the size, shape, and depth of the indentation, and (5) the nature of the currents, tidal or otherwise.

Whatever the relative value of these several factors, there will come a place in the rather slightly disturbed water of the indentation where much or all of this material will come to rest. Some will lodge upon the shore, some upon the bottom, and some may go far into the indentation. But the greatest part will come to rest at the point where the average transporting power of wave wash or current is so checked that it can no longer move the average-sized fragments.

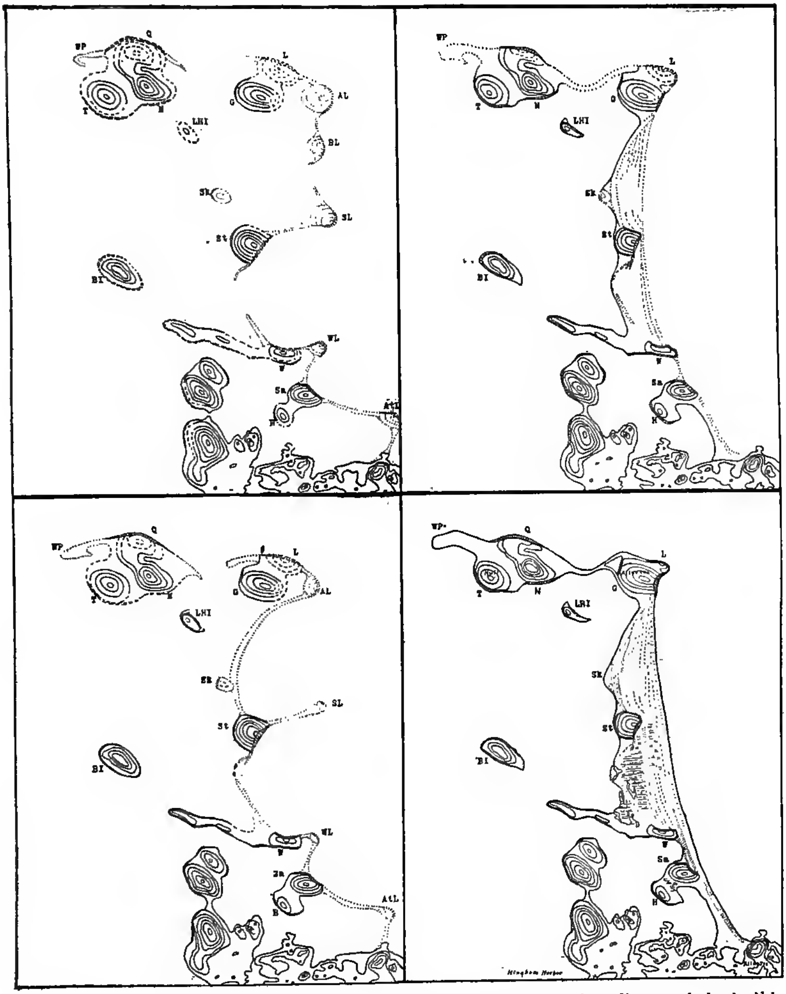


FIG. 238. — Four stages in the cutting of cliffs, the destruction of drumlins, and the building of beaches which tie islands to the mainland at Nantasket, Mass. (Johnson.)

This point is usually not far from the mouth of the indentation, but slightly within the mouth.

Bays Closed by Bars. — It is as a result of this process that the mouths of bays and other indentations on an irregular coast are being closed by deposit. In some cases, bay mouths are completely shut in by bars of sand, or pebbles, or boulders; in others the process is only partially completed. On some coasts, especially sandy coasts where waves and currents have abundant material, the bars across bays are a serious obstacle to navigation, and much expense is required to keep a ship channel open. Most good-sized bays cannot be completely closed to tidal currents, and the outflow of water from the land must maintain an opening; but such an opening may be shifted both in position and depth.

Tied Islands. — Rock fragments wrested by the waves from the shores of an island are driven along the coast, and often come to rest in the quieter water in the lee of the island. There a bar is built, which ultimately may rise above high tide level. If the island is not far from another island, or from the mainland, the bar may extend to the neighbouring land, tying the island to it. Such *tied islands* abound along drowned coasts, as in Maine. Sometimes the island is tied by a single bar, perhaps partly submerged, sometimes by two bars, one from either side of the island, enclosing a lagoon between; with the filling of the lagoon the connecting bar becomes broad and the island forms the tip of a peninsula, whose rock is made of marine sediment, — sand, pebbles, or boulders. Gibraltar is an instance of such a tied island, forming a peninsula projecting from the Spanish mainland, at first as a broad, low, flat bar and at the end rising abruptly as a rocky hill.

Irregular coast lines abound in instances of tied and partly tied islands, and of bars across bays or other indentations in various stages of development (Figs. 237, 238).

Spits and Cuspate Forelands. — At times conditions exist as a result of which sediment is driven outward from the coast in such amount as to form a sand or gravel point, called a *spit.* At a bend in the coast, for example, wave wash from opposite directions may be so nearly in balance as to cause deposit at the bend, and then the coast grows outward. This outward growth may give rise to a pointed spit, or to a rounded point, or to two bars meeting either in a point or in a curve, forming a *cuspate foreland* (Fig. 239). These shoreline features may also develop as a result of the action of currents; and they may form where there is excessive sediment supply from the land, as on delta margins. They are an expression of the activity of the waves or currents in disposing of the sediment load consigned to them.

Small spits develop in many lakes, as at Crowbar Point in Cayuga Lake; in indentations of the coast line as in the so-called Bras d'Or Lakes of Cape Breton Island (Fig. 240); and also along sand coasts. Cuspate forelands are also found in the Bras d'Or Lakes; and Capes Hatteras, Fear, and Canaveral on the eastern coast of the United States are large instances on an exposed ocean coast.

Offshore Bars. — From headlands supplying abundant sediment, or from river mouths which pour much sediment into the sea or lake, bars often extend in either direction, or in only one if the waves or currents come from a single direction. This is well illustrated on the New Jersey coast, where, from the cliffs of unconsolidated deposits, the waves are receiving so great a supply of sediment that the surplus is driven along the coast, both southward and northward, forming *offshore bars*. The one extending northward is called Sandy Hook,

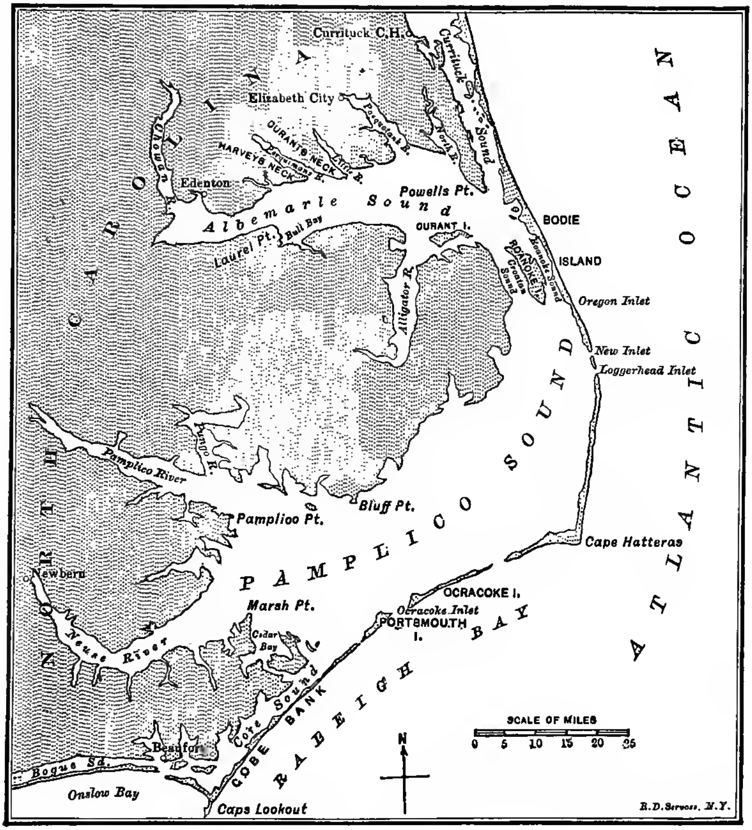


FIG. 239.—Cuspate forelands of Capes Hatteras and Lookout.

and it has grown part way across the mouth of New York harbour. Much expense in dredging is necessary to maintain a passageway across the submarine extension of this deposit, and the ship channel winds in a devious course across it.

A similar condition exists along the eastern shore of Cape Cod. The waves are eating back into the unconsolidated deposits at and near Highland Light, and the débris is driven both northward and southward. That to the north forms the rounded end of the cape. That to the south extends out under water, supplying sand to the shifting Nantucket Shoals, one of the most dangerous parts of our eastern coast.

By the growth of such bars, bay mouths are enclosed and lagoons are formed between the mainland and the coast. On the land side of these lagoons an old sea cliff may sometimes be seen, as in New Jersey, formed when the waves beat against the mainland, before the protecting bar was built offshore. The bars are the seat of steady wave work and change, for the waves and currents are engaged in the task of perfecting them; and if this were the only work, the bar would be continuous. As a matter of fact it is broken, sometimes into linear islands, sometimes merely by the gaps where the land water escapes from the enclosed bays or lagoons. In the latter case waves and currents work steadily to completely seal the bay; while the inflowing and outflowing currents work to maintain a passageway across the bar. As a result of these opposing tendencies, the form of the bar, and the form and depth of the breach in it, are subject to notable change. This is well illustrated along the New Jersey coast, where

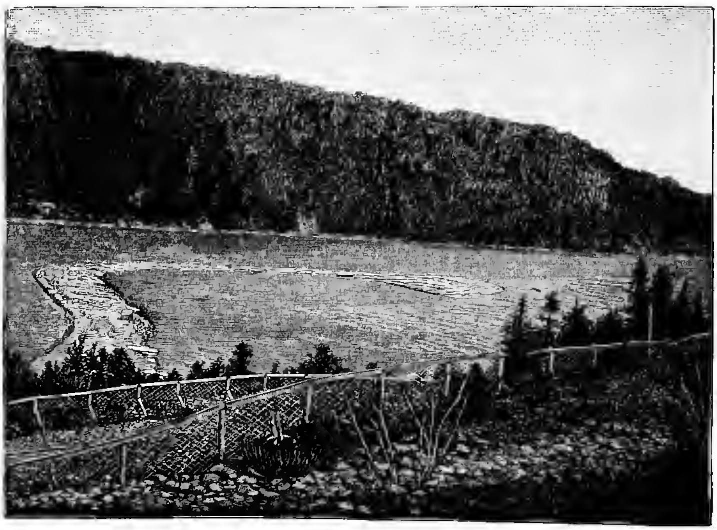


FIG. 240. — A hooked spit or hook in one of the Bras d'Or Lakes in Nova Scotia.

the sites of houses and hotels of a few decades ago are now occupied by an inlet; while the former site of inlets is now occupied by bars.

Hooks. — One result of the conflict between the advance of sediment in a bar or spit, and the currents is the turning, or curving of the end, forming what is called a *hook*, such as Sandy Hook and the hooked end of Cape Cod. Similar hooks are common in lakes, and at the ends of bars partly enclosing bays. The hook form is the result of the inability of the transporting agent to drive forward the end of

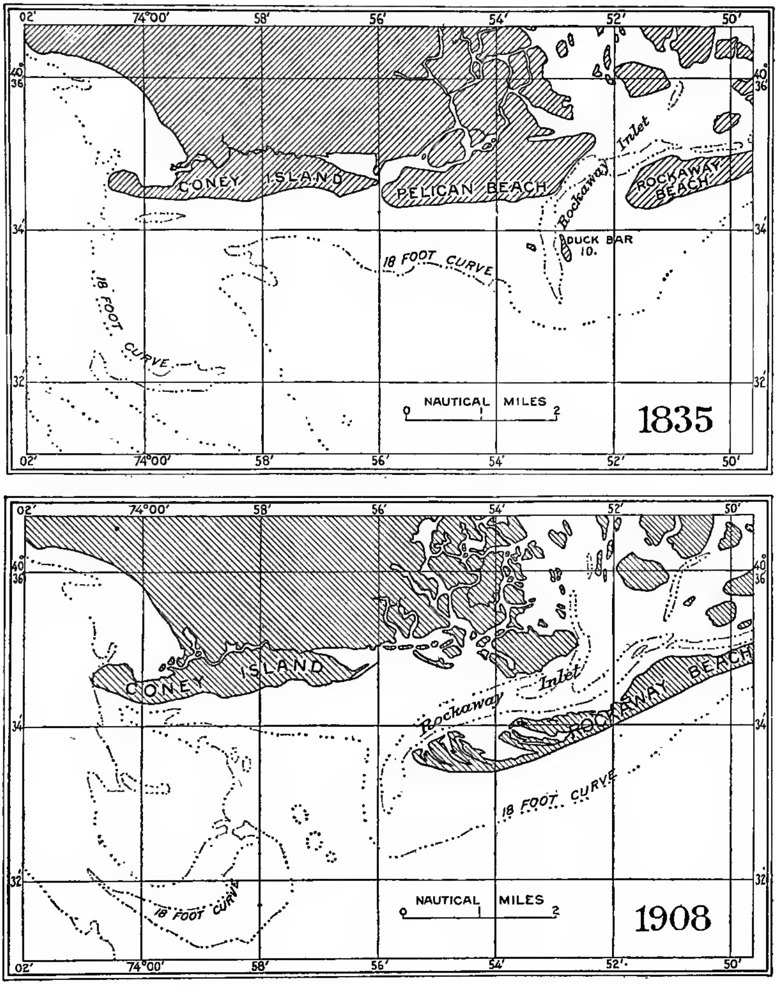


FIG. 241.—The beach at Rockaway, Long Island, where a hooked spit advanced westward over three miles between 1835 and 1908. (Putnam.)

the spit or bar as fast as cross currents or waves can push the sediment in another direction. The tendency to curve the end of the bar may be present all the time during the bar growth; but it becomes effective in actually developing the hook form (*a*) when the distance of the bar end from the source of supply becomes so great that the cross currents or waves can dominate, or (*b*) when the size of fragment diminishes to a size which the cross currents can more easily handle,

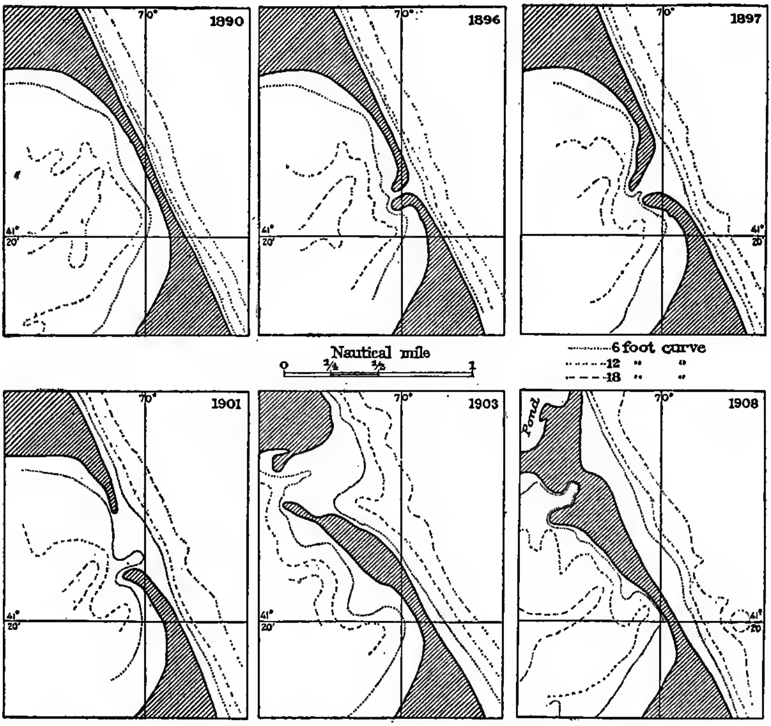


FIG. 242. — Shoreline changes at the Haulover, Nantucket Island. (Putnam.)

or (*c*) when, by the constriction of an inlet, the cross current is given sufficient velocity to dominate in sediment movement (Figs. 241, 242).

Barrier Beaches and Lagoons. — Some low-lying coasts are bordered by fairly continuous *offshore sand bars* or *barrier beaches*, or *sand reefs*. This is true, for instance, of a large proportion of the coast south of New York, and is particularly well illustrated along the Texas coast, where there is a continuous sand bar from the mouth of the Rio Grande fully 100 miles northeastward (Fig. 243); beyond this the bar continues, though broken here and there by inlets. A part of the supply for such beaches comes from river sediment; and, as we have seen along the New Jersey coast, a part may come from cliffs against which the waves are cutting. But a barrier beach may develop without any such source of sediment if the sea bottom is shallow and sandy. This is the case on the coast south of New York.

Along such a coast the waves come in contact with the shallow bottom and push the sand before them, finally raising it in a barrier beach at the appropriate distance offshore. If no additional supply is obtained, the barrier beach will slowly migrate landwards; but if sediment is supplied by rivers, it may grow outward. The pushing back of the barrier beach is due partly to the fact that the sand is ground finer and carried away by the waves or currents, and partly to the action of the wind, which drives the sand from the beach into dunes back of the beach or into the lagoon behind the beach. Ultimately the beach might be pushed back to the land margin and the waves then attack the land itself.

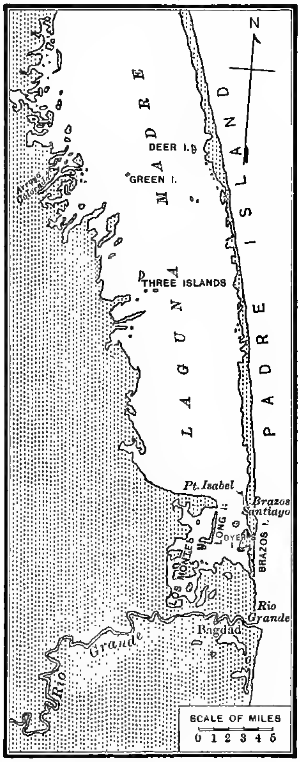


FIG. 243. — Offshore bar and lagoon on the coast of Texas.

The process of pushing back the barrier beach is, however, a slow one, and, where sediment is supplied by rivers, the rate is still further decreased. It therefore is commonly the case that the shallow lagoon behind the barrier is slowly filled with sediment, some from the land streams, some brought from the beach by the wind, and some the remains of plants and animals living in the lagoons.

On the coast of Brazil, Branner has described *stone reefs*, which represent another termination of the history of the offshore bar. In this case they are converted into reefs of solid rock by the carbonate of lime from calcareous skeletons of animals and plants buried in the sand, which cements the sand grains of the upper 10 to 12 feet of the reef into sandstone or quartzite. These stone reefs follow the shores of northeastern Brazil for about 1250 miles (Fig. 244). They are 450 feet or less in width and are interrupted by channelways at distances of from a few hundred feet to $8\frac{1}{2}$ miles. They have been modified by the waves, which have swept away the loose unconsolidated material, making the borders more broken and angular than in ordinary offshore bars. There is a similar reef at Jaffa in the Mediterranean; but the lack of similar climatic conditions seems to have prevented the formation of stone reefs elsewhere.

Uses of Barrier Beaches by Man. — The barrier beach is built to the height reached by the highest waves, and then, by wind action, still higher, sometimes 50 to 100 feet above mean sea level. Fishermen and summer residents build homes on the sand; in the sea islands of southern United States cotton is raised; at Galveston there is an important seaport city, and at Atlantic City, a popular summer resort (Fig. 230).

The open coast is straight and smooth as a result of the diagonal reach of the waves and the currents, and it is surf-beaten, as the waves of the open ocean break upon it. The lagoon coast is far more irregular, and the waters there are both shallow and protected. Being commonly no more than 5 to 10 feet in depth, the lagoons are not navigable to large boats; but they deepen where they merge into bays indenting the land; and opposite the mouths of such bays there is commonly a break in the bar, or an *inlet*. It is on the margin of such an inlet that Galveston is located; and by building jetties, thus further confining the current of water that flows through the inlet, the entrance to the harbour has been deepened so as to admit large ships (Fig. 245). The harbour of Pernambuco, Brazil, is protected by a stone reef.

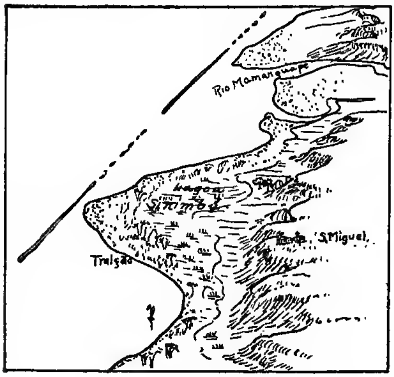


Fig. 244. — Stone reef off the coast of Brazil. (Branner.)

Development of a Coast Line

Structure, Process, and Stage in Shorelines. — As in the case of every land form, the evolution is influenced (*a*) by the material worked upon, (*b*) by the forces in operation, (*c*) by the time element, or, as put by Professor Davis, by *structure*, *process* and *stage*. We have already seen that, given variation in the forces, there results difference in the form; and that there is variation in the shoreline according to the material worked upon. It is equally true that there is a great difference in shoreline form according to the stage of development, for shorelines, like other land forms, pass through a life history. This could be illustrated by considering the shore forms in detail — the cliff, the sea cave, the hook, etc.; but we will go no further than to consider it in its more general application to a coast line as a whole.

Young Consequent Coasts. — At its beginning a shoreline will have that form which is the consequence of the line of contact of sea

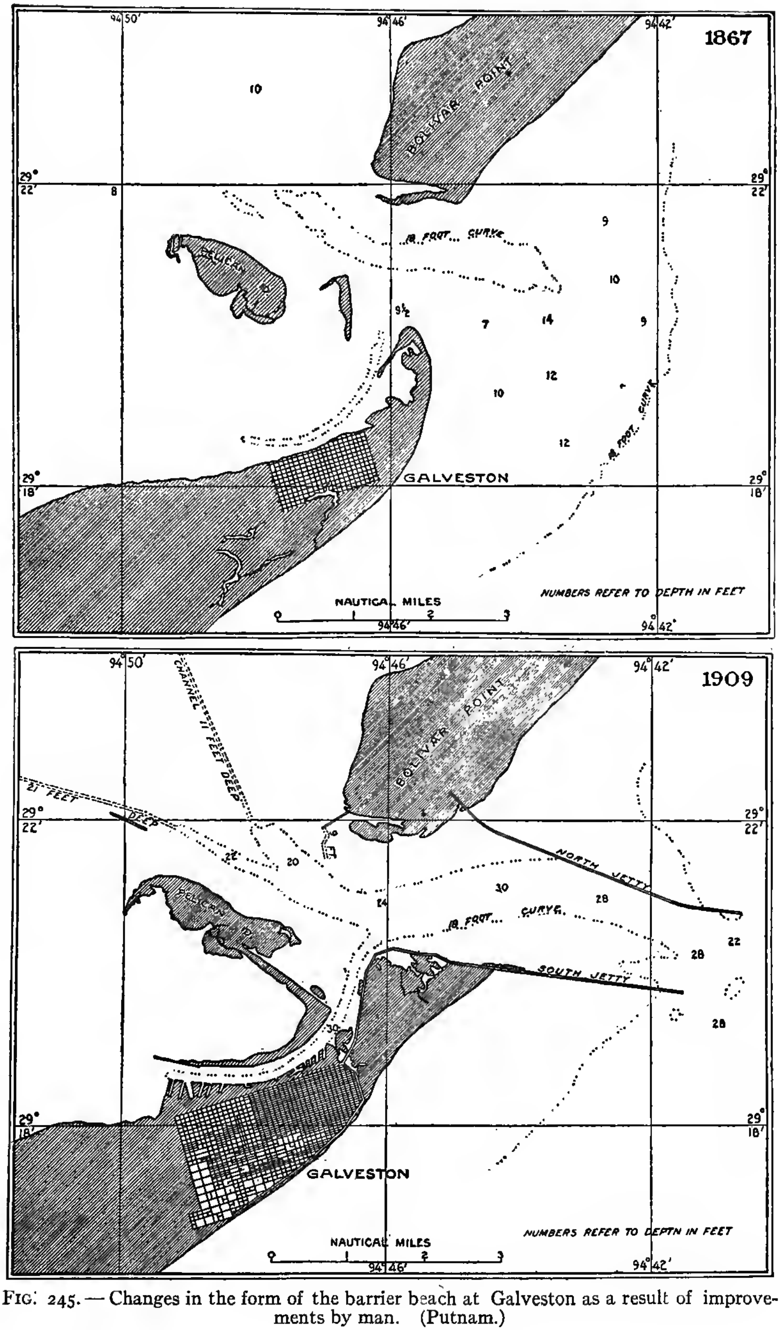


FIG. 245. — Changes in the form of the barrier beach at Galveston as a result of improvements by man. (Putnam.)

and land — a consequent form (Fig. 246). Conceivably the consequent shoreline might be straight, but it would be far more likely to be irregular, and, on a drowned hilly land, it may have an extraordinary degree of irregularity. With the passage of time there is the tendency toward the development of regularity both by cut and by fill. The headlands are cut backward, the bay mouths have deposits made across them with materials derived from the waste of the sea cliffs, and the inlets tend to become filled by deposits from the land, from the sea, and from organic remains. Locally minor irregularities may result, such as spits, hooks, and cuspate forelands, but these are only the temporary exceptions.

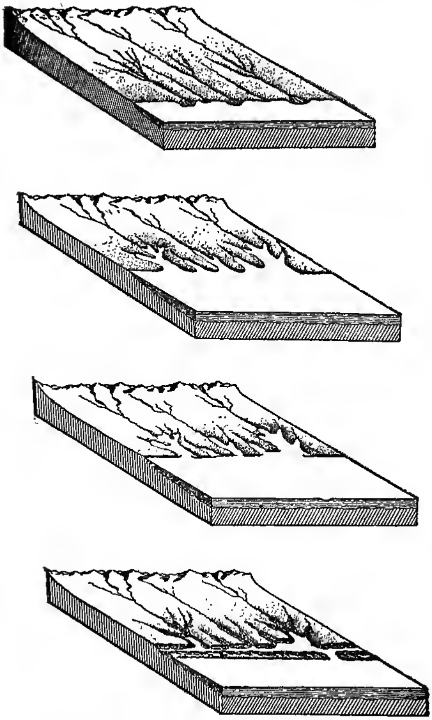


FIG. 246. — Block diagrams to show life history of a coast in weak rock, as in Maryland and New Jersey: (1) coastal plain with shallow valleys and small deltas; (2) embayed coast produced by sinking of the land; (3) low cliffs and short bars produced by wave work; (4) offshore bar, resulting from later wave work and salt marsh in lagoon. A fifth stage for old age of this coast would show the offshore bar pushed back, the inner bays sealed by bars, and the coast straight and simple. For the life history of a coast in resistant rock see Fig. 232.

Mature Coasts are Straight. — Given time, the most irregular coast line would become straightened under these influences; but then irregularity might be introduced by the outward projection of deltas at the stream mouths. These would form actual points or peninsulas if deposit exceeded the power of waves and currents to remove; or rounded points if the excess of sediment were slight; or offshore sand bars if the waves and currents were able to give it wide distribution.

Factors Influencing Rate of Development. — There will be a notable difference in the rate and in the nature of the development of coast lines according to (1) the nature of the rock, (2) the direction of waves and currents, (3) the intensity of waves and currents, (4) the depth of water, (5) the height of the land, (6) the amount of sediment supplied from the land. It may even happen that the initial coast line is rapidly straightened, the old land being faced by a barrier beach of new land, as along the southern coast of the United States — such a straight coast, backed by an unfilled lagoon, is really a young coast, although straight where the waves have thrown up an offshore bar of new land.

Where wave action is vigorous, and supply is not excessive, there may be very notable change in the coast, even in very brief periods of time. This is well illustrated at Cape Cod, where the waves have actively cut back the cliff near Highland Light, and a straight beach has been made, both to the north and south, along which the sediment is driven. As the cliff has moved backward, the bar to the north has moved outward as from a fulcrum at Highland Light cliffs, and the outward movement has also extended to the hooked end of the bar. The present curved outline of the north end of Cape Cod represents the form of equilibrium assumed between present supply and transporting forces from the cliff of to-day. In earlier times, when the cliff was farther out, other curved outlines of smaller radius were developed and can still be traced; they represent the equilibrium of forces, supply, and cliff position of former days. The whole north end of Cape Cod has been made by the transportation of sediment from the receding cliff, some of it blown inland to form sand dunes.

Old Coasts Rare. — As a whole the coast lines of the world are in a stage of youth, for, as has been already pointed out, the relation of land and sea is not long maintained without change. An old coast line would be a straight one, no matter what its initial irregularity, with delta projections opposite the stream mouths.

The Influence of Animals and Plants

Constructive, Destructive, and Protective Effects. — Both animals and plants exert an influence upon coast lines either through (1) constructive, (2) destructive, or (3) protective effects, or (4) by a combination of two or all of these.

The constructive effect is the result of the deposit of more or less indestructible organic remains, sometimes merely as parts of deposits of other origin, as in the case of sand beaches and mud flats, in which shells and other organic remains are included. In other cases certain types of organisms are so abundant that they give rise to purely organic deposits, for example in coral reefs.

The destructive work of organisms is an aid to the modification of coast lines. In sand beaches and mud flats, for example, there are burrowing animals which make and leave openings in the sediment, and even on rocky coasts there are organisms which eat directly into the rock, or aid in its destruction by indirect means. As an illustration of this type of work may be mentioned the burrowing shells which excavate cavities in the limestone rock, of which the shell *lithodomus* in the Mediterranean is an instance (Fig. 262).

Many coasts receive effective protection from organic life. This is true in tropical waters where fringing coral reefs receive the blow of the breaking wave, while the coast of the mainland itself is faced by the quiet lagoon. It is also illustrated on many rocky coasts where seaweed and other organisms cling to the rock, both in the zone of the breaking wave and on the shallow offshore platform. On the rocky coasts of temperate latitudes the seaweed forms a mat of tough, rubbery, organic tissue, against which a large measure of the wave-blow is expended. It is probable that without this protective influence the rate of wearing back of such coast lines would be far more rapid than is the case.

While there are a multitude of ways in which organisms aid in a constructive, destructive, or protective way, sometimes with local effects of marked importance, there are three kinds of organic work which give rise to important and well-recognized coast forms. Two of these, salt marshes and mangrove swamps, are the result of the influence of plant growth, while the third, coral reefs, are due to the effect of animal life.

Salt Marshes. — Salt marsh plants cannot grow where the waves break, but in the protected lagoons and estuaries of the cool temperate

Fig. 247.— A salt marsh in eastern Massachusetts at mid-tide. At high tide it is completely submerged.

region there are extensive plains called *salt marshes.* Their surfaces rise about to the level of the high tide, and over them the salt water flows at intervals. These marshes are traversed by a series of mud-walled channels, into which the tide rises, and out of which the salt water is drained from the marsh area at low tide. Upon the surfaces of the marshes (Fig. 247) there is vegetation, consisting of a variety of plants adapted to life in a salt soil. The marshes are growing and filling the estuary or lagoon by deposit of sediment brought by the tidal currents, and they are growing upward by deposit during the periods of overflow and by the accumulation of organic remains.

These salt marsh plains, therefore, consist of inorganic sediment, of the remains of the salt marsh grasses, and of animals that live in this habitat. In the deposit of sediment the marsh plants aid indirectly in so checking the currents as to induce deposit. Ultimately by such accumulation a lagoon or estuary may become filled from side to side, with perhaps the single exception of one or more channelways through which the tide passes. Ultimately the surface will be raised to, or even above, the level of the tide. On extensive salt marshes there are areas so low that they are covered by every tide, others which are reached only by the highest spring tides, and even sections to which the tide no longer reaches.

Utilization of Salt Marshes. — By a slight uplift of the land such a marshy plain may, after proper drainage, become good agricultural land; or, by building embankments to shut out the tide, man may reclaim marsh lands which have not yet risen into the dry land condition. In this way extensive tracts of salt marsh have been reclaimed in England, in Holland, and in Nova Scotia, the so-called land of Evangeline in Nova Scotia being salt marsh reclaimed by the French Acadians. As yet little has been done toward the reclamation of salt marshes in the United States, but, in the thousands of square miles of sand marshes along the eastern coast, there are many areas which will doubtless be reclaimed when land values are sufficient to warrant the expenditure.

Mangrove Swamps. — In the warm waters of the tropical and subtropical lands the mangrove tree, represented by many species, has adapted itself to life in the quiet waters of lagoons and estuaries. In such climates, therefore, the mangrove replaces the swamp grasses, forming *mangrove swamps*. The mangrove tree rests upon a branching base with roots extending through the marine soil (Fig. 248); from the branches of the tree other roots descend to the sea floor, thus giving rise to an almost impenetrable thicket of branching tree roots, and furnishing to the tree great stability, although growing in unstable soil. The cigar-shaped fruit, floating with the root-end downward and germinating when in contact with the bottom, sends up a shoot, which adds to the root tangle of the mature trees.

In such a tangle the currents of ocean water are checked and sediment deposit is assisted; while to this deposit is added the decaying remains of the mangrove itself and the shells and other durable parts of marine organisms. Thus the mangrove swamp extends its area, giving rise to a characteristic coast form in the quiet tropical waters.

Coral Reefs. — A multitude of marine animals abstract mineral matter from the sea water and incorporate it in their shells or skeletons, which, upon their death, remains as a part of marine deposits. In some situations along coast lines the deposit of sediment is so limited and the abundance of shell-building animals is so great that shell deposits are formed. Thus there are shell banks and oyster beds along some coasts.

In tropical waters the abundance of shell-building organisms is far greater than in temperate latitudes, and there are some species

FIG. 248. — Mangrove swamp on the coast of Florida.

which thrive in such abundance that their remains form extensive deposits. Of these the reef-building corals are the most noteworthy, though upon coral reefs there are, besides corals, a multitude of other shell-making animals, and also lime-secreting plants, notably the calcareous algæ.

Conditions Requisite for Coral Growth. — The reef-building corals and their associates are not uniformly deposited throughout the warm ocean waters, for their growth in sufficient abundance to give rise to coral deposits depends upon a delicate balance of favourable conditions, among the most important of which are the following: (1) The temperature of the water must be high and in no case less than 68° F., even this temperature being too low for the most abundant coral growth. (2) The water must be shallow, with a depth not exceeding 90 to 120 feet. Although it is true that shell-building animals live at greater depths, the reef-building corals do not thrive. They grow best in 35 to 50 feet of water. (3) The water must be normally saline, and, therefore, along the ocean margins where the water is freshened by the inflow of rivers, reef-building corals do not thrive. (4) The water must be clear and free from abundant sediment, therefore, where muddy rivers enter the sea or where wave work causes muddy coastal water, coral reefs cannot develop. (5) There must be sufficient food supply to nourish the abundant life of the coral reef. The most favourable condition for this purpose is the presence of steadily flowing ocean currents, which are ever sweeping up to the stationary organisms the needed food supply. Coral reefs are extensive on the east coasts of Africa, central America, and Australia, which are bathed by warm currents, while on the west coasts of these lands the corals occur only in scattered patches.

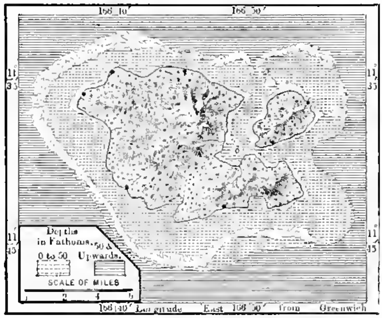


Fig. 249. — Barrier reef in the Marshall Islands, Pacific Ocean.

Abundance of Life on Coral Reefs. — Where all these conditions are met, the abundance of coralline and other marine life is so great that rapid growth occurs and reefs develop. The abundance and variety of life on such a coral reef is almost inconceivable, for each branching coral or each coral head is the home of scores of hundreds of individuals, or *polyps*, each spread out flower-like, beyond its stony home, exhibiting a surprising variety of form and colour. Each animal is engaged in the double process of seizing food as it passes and abstracting carbonate of lime to build the cells in which it lives. Associated with corals are variously coloured sponges, calcareous algæ, and a great variety of mollusks and crustaceans. Every square inch of surface is inhabited by some form of life, and often there are two or three tiers of organisms, the vast majority of which have, as a part of their structure, either carbonate of lime or silica which is aiding in the upbuilding of the reef. It has been estimated that the corals have built up the reefs in Florida over 40 feet in 1000 or 1200 years.


Fig. 250. — An atoll in the Carolina Islands, Pacific Ocean. (E. S. Holden.)

Fringing Reefs. — Along some coasts there are extensive fringes of coral reef known as *fringing reefs*. These reefs parallel the coast at a variable distance, according to the depth of the water, and around them the ocean waves break, while between the reef and the land is a protected, shallow lagoon, in which the growth of the lime-secreting organisms is less rapid because of the more limited food supply. There is such a reef along the coast of southern Florida.

Barrier Reefs and Atolls. — Fringing reefs are relatively close to the coast, but islands in the open waters of the warm oceans are surrounded at a little greater distance by a *barrier reef* which has grown outward upon its own talus. The greatest of all the reefs is the Great Barrier Reef, which extends along the eastern coast of Australia for a distance of 1250 miles with a width of from 10 to 90 miles. There are also reefs upon shallow banks, like the Florida Keys. In the tropical Pacific and Indian oceans are circular reefs known as *atolls* (Fig. 250).

Darwin's Theory of Atoll Formation. — There has been much discussion concerning the origin of atolls, and as yet it cannot be said that their cause is definitely established. Both Darwin and Dana

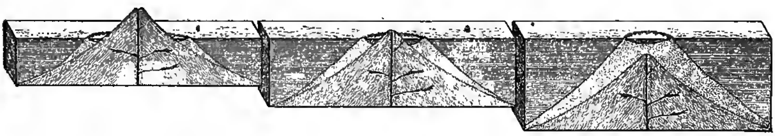


FIG. 251. — Block diagrams to show fringing reef (left), barrier reef (middle), and atoll (right) around sinking volcano, as proposed by Darwin.

put forward the theory that these atolls are the descendants first of fringing, then of barrier reefs around oceanic islands, which have disappeared by slow subsidence while the fringing reef continued to grow. The difficulty of believing in such widespread sinking of the sea bottom at so slow a rate as the upward growth of the reef would demand has, to many, seemed very great (Fig. 251).

Daly has suggested a relationship between the coral reefs found on flat ocean platforms less than 300 feet below sea level and the lowering of sea level by the temporary locking up of water in the ice of the continental glaciers. This involves marine planation of the platforms, a slow increase in depth of water, but no change of level of the land.

An 1114-foot boring in the coral reef of Funafuti does not seem to give conclusive proof of the correctness of the Darwin-Dana hypothesis, which, however, is supported strongly by the presence of drowned valleys at the borders of the island inside certain barrier reefs (Fig. 249).

Murray's Theory of Atoll Formation. — The rival theory, proposed by Murray, has seemed to many a more probable explanation of the peculiar atoll form. This theory is that while some atolls may be the result of slow subsidence with accompanying upgrowth of fringing reefs, others, and perhaps the majority, have developed upon submarine shoals, such, for example, as a volcanic peak which did not rise to the surface, or upon the platform of an island destroyed by wave erosion. The circular form of the atoll and the lagoon which it encloses are upon this theory explained as a result of the more rapid growth of reef-building corals on the exposed outer side, and of the more rapid solution of calcareous remains in the lagoon than the growth of organisms can counterbalance. Some atolls occur where uplift rather than sinking has taken place.

Evidence from Serpula Atolls. — The process by which this development of atolls is said to have proceeded is illustrated on the shores of Bermuda, where planed-off stacks have furnished platforms upon which shell-building marine organisms have taken hold, especially the genus *serpula*, which lives in the calcareous tube that it secretes. In these situations the serpula grows in the zone of wave attack over the entire platform, but it grows more abundantly on the outer side than on the inner, with the result that, by its growth, a platform is built into a saucer shape with an atoll-like rim, enclosing a small lagoon, the diameter of the entire area of the serpula atoll being only a few yards (Fig. 252).

Fig. 252.—Serpula atolls, Bermuda.

The Life History of Coral Reefs. — When a coral reef rises into the zone of vigorous wave attack, it is itself subjected to partial destruction by solution and by mechanical erosion. It may, therefore, happen that the balance between upward growth and destruction by wave attack will be about equal and the upward rise of the coral reef be checked. It cannot in any event be built above the level of the lowest tide, for the coral animals cannot stand exposure to the air. The fragments torn off by the waves may either be driven into the lagoon behind the reef, or upon the inner shore of the lagoon, or it may even be raised to form a coral beach upon the reef crest itself. In the Bermuda Islands fragments of coral torn from the fringing reef, together with shells driven in from the shallow offshore waters, accumulate upon the beaches of the islands and are there ground up into coral and shell sand. Some of this is then drifted inland by the winds, forming shell and coral sand dunes, as already described. On the atolls, and on the other coral reefs, the beaches that are made upon the reef crests likewise serve as a source of supply of coral sand which the winds drive above the reach of waves. It is because of this coöperation of the wind that many coral islands have been made habitable. Some of those in the south Pacific Ocean support a large native population. The people live chiefly on fruits, especially the cocoanut, and fish for pearls in the lagoons of the atolls. In other cases uplift has raised the coral above sea level.

Islands

Constructional Islands. — Islands are sometimes classified as *continental* and *oceanic;* but this does not take into consideration any essential element either in origin or form. The better classification is into the two divisions: (*a*) constructional and (*b*) destructional. It would be possible to subdivide each of these two divisions into a great variety of kinds according to origin, but it will serve our purposes to merely illustrate the two major divisions. Coral islands are constructional, and so also are volcanic islands and the higher parts of growing mountains, such as the West Indies, the Philippines, and the East Indies. Islands resulting from deposits at river mouths or in connection with the growth of sand bars are also constructional.

Destructional Islands. — Islands of destructional origin include those which are formed by the subsidence of the land, leaving the higher parts isolated. In this class are also included those islands which develop as the waves cut back coast lines, leaving insular stacks.

Life History of Islands. — In the life history of an island there is always involved the attack of the agents of erosion which are engaged in an effort to remove it. If, however, it is of constructional origin, the attacks of these agents may be less effective than the operation of the processes which are forming it. Thus, for instance, a coral island may grow faster than the waves can remove the coral fragments, or a sand bar may continue to grow in the face of continuous and vigorous wave attack, or a volcanic island may steadily extend its area by eruption of lava or ash, although exposed to the full violence of open ocean waves. But if the constructional processes cease, or if they become so diminished that wave attack exceeds accumulation, the life history is then one of destruction. Subaërial agents are engaged in removing material from its surface, while oceanic agents are attacking its periphery. The ultimate fate of such an island would be reduction below the level of the sea. If near the mainland, one stage in the process of destruction of the island may be the tying of it to the mainland by a sand bar, temporarily transforming it to a peninsula.

Bays and Harbours

Bays Due to Subsidence. — The great majority of bays, harbours, estuaries, and other indentations of the coast line are the result of subsidence of the land, admitting the sea into the lower portions of the land.

Bays Due to Uplift and Other Causes. — Some indentations are, however, also caused (*a*) by irregular uplift, as during mountain elevation, (*b*) by volcanic action, (*c*) by glacial erosion, or (*d*) by the development of coral reefs or sand bars.

Variations in Form. — The form and depth of such indentations varies greatly, according to the surrounding conditions. Some harbours are broad, branching, and irregular, as where the irregular mountain growth has been in progress, or where depression of the land has admitted the sea into an irregular valley. Others are long, narrow, and linear, as in the case of fiords whose form is due to glacial erosion, and in the case of river mouths. Some even are circular, as (*a*) where volcanic craters are breached so as to admit the sea, and (*b*) the lagoons of the circular atolls. Some are deep and free from shoals, as along the fiorded coast, while others are shallow and interrupted by islands and shallow patches, as in the lagoons around coral reefs and sand bars, and in indentations resulting from subsidence of an irregular land. Man often creates harbours where there is no good protection from the waves (Pl. VI).

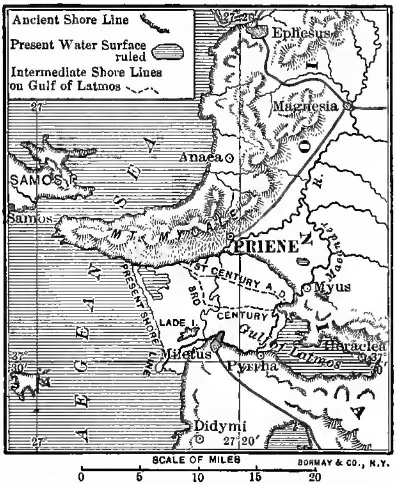


Fig. 253. — Changes in coast of Asia Minor where a shoreline has advanced seaward 10 miles since the time of Christ.

The Destruction of Harbours. — Whatever the origin and form of an indentation along the coast line, it is subjected to a double action which tends towards this extinction, (1) through deposit, (2) through the closing of the entrance. The rate at which this extinction progresses varies with the area and depth of the indentation, and with the supply of sediment which is coming into it. Some shallow bays are soon filled, and their mouths quickly close; others resist the processes of extinction through long periods of time. One cannot doubt, however, that the continuation of deposit by the many streams that are entering so large a body as the Gulf of Mexico would ultimately succeed in completely closing it. In times past, deposit has filled large areas of interior United States, and in more recent times the deposits of the Mississippi and its tributaries have filled a bay which extended as far up the valley as Cairo in southern Illinois. The broad, fertile valley of the Po in Italy is a river-filled bay head, the normal extension of the Adriatic Sea, and the valley of Tigris and Euphrates in Mesopotamia is the filled head of the Persian Gulf. The continuation of the process of extermination of these indentations is now so rapidly in progress that notable changes in the position of the coast line have occurred since the days of the Roman Empire (Fig. 253), and even since the Middle Ages. That some indentations are not filled is an indication of their relative youthfulness, for they are the seat of deposit of sediment both from the land and from the agencies of the ocean.

Elevated Coast Lines

Features produced by Change of Level of the Land. — The instability of the relation between land and sea is so great that a large part

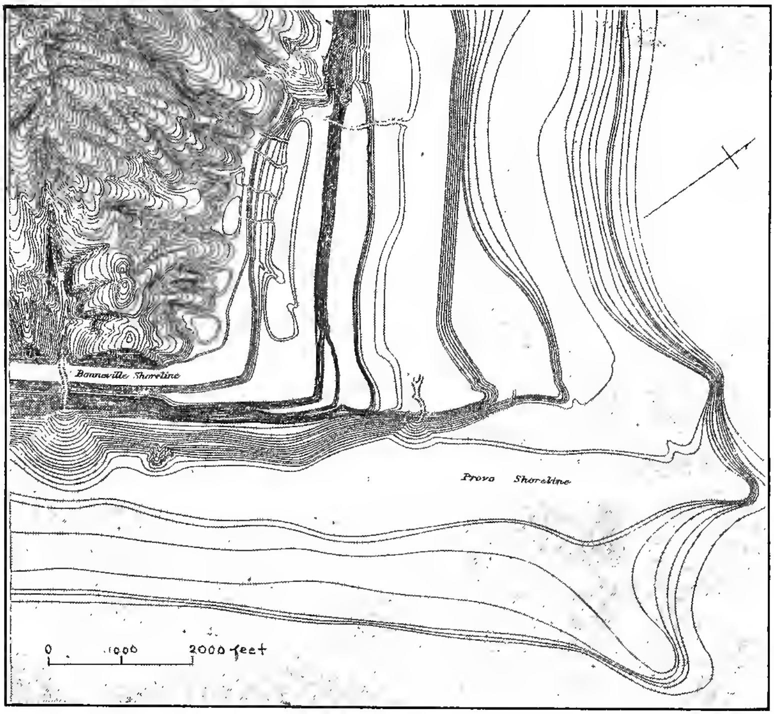


Fig. 254. — Shorelines of Lake Bonneville. (Gilbert.)

of the coast line gives evidence either of recent subsidence or of recent elevation. It has already been shown that, by subsidence, an irregular coast line is produced. By elevation the sea bottom is raised into the air and the coast line of that stage becomes a feature of the dry land. Wave-cut cliffs, beaches, sand bars, and clays with marine organisms entombed are then exposed to view.

Abandoned Shorelines near the Sea. — Such elevated shorelines are revealed along the coast of northeastern North America, from Boston northward to northern Labrador and to the islands further north. Similar uplifted shorelines are clearly exhibited along the west coast of Scotland and along the Norwegian shore. In Norway the uplifted strip of sea bottom forms some of the best farm land along the fiorded coast, and back of the farm lands rise wave-cut benches in which wave-eroded chasms and sea caves are still preserved, showing the recency of the uplift (Fig. 233).

Abandoned Shorelines in the Interior of the Continent.—Shorelines of similar character are found around the margins of the Great Lakes, where they were formed on the coast of the temporary lakes during the closing stages of the Glacial Period. Among the most perfect abandoned shorelines are those which lie above the Great Salt Lake, formed during the expanded stages of Lake Bonneville. From a study of such shorelines a clear idea of the nature and origin of shoreline features can be gained, and it was from a study of the Bonneville beaches (Fig. 254) that we have obtained the best study of shorelines that has ever been published — the classical work of G. K. Gilbert.

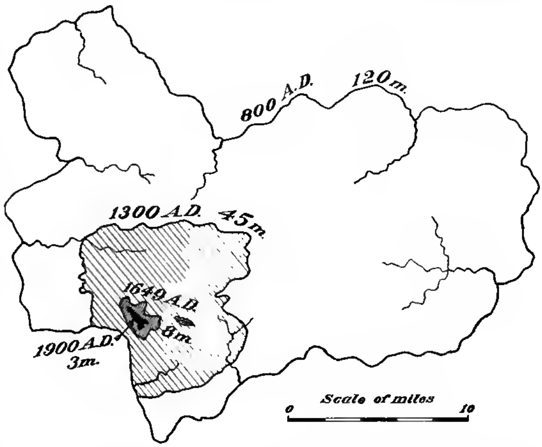


FIG. 255. — Map showing four stages in the destruction of the island of Heligoland off the coast of Germany. The figures give the circumference in miles at various dates.

SEA COASTS AND MAN

Aside from such obvious relationships of man to sea coasts as have been already alluded to, his use of harbours, his fishing in shallow arms of the sea, and the perils to navigation through the wrecking of vessels upon reefs, the contact of sea and land touches his activities at many other points. The erosion of the coast may cut away his land, as in southeastern England, where whole farms and villages have been washed away in the last few centuries, the sea cliffs retreating from 7 to 15 feet a year, or on the coast of Holland, where a Roman castle, built on dunes $1\frac{1}{2}$ miles back from the sea, was in 1694 a half mile out in the sea, or in Heligoland, where an island has been tremendously reduced in area (Fig. 255), or Sharp's Island in Chesapeake Bay, which was reduced by wave erosion from an area of 438 acres in 1848 to 53 acres in 1910. Man's greatest defiance of the sea is probably the building of the Florida coast railway which traverses coral reefs and the intervening stretches of open water with a concrete causeway. It is over 100 miles long, extending from the mainland of Florida to Key West (Fig. 256).

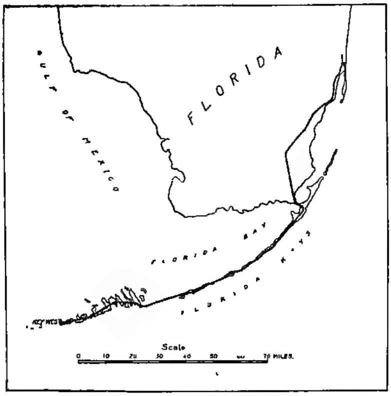


Fig. 256.—Map showing the railway to Key West.

References to Literature

C. Abbe, Jr. The Cuspate Capes of the Carolina Coast, Proc. Bost. Soc. Nat. Hist., Vol. 26, 1895, pp. 489–497.

A. Agassiz. Notes from the Bermudas, Amer. Journ. Sci., Vol. 147, 1894, pp. 411–416; Coral Reefs of the Tropical Pacific, Memoir 28, Mus. Comp. Zoöl., 1903, 410 pp.; The Elevated Reef of Florida, *ibid.*, Vol. 28, 1896, pp. 29–62.

W. W. Atwood and J. W. Goldthwait. Physical Geography of the Evanston-Waukegan Region, Bull. 7, Ill. Geol. Survey, 1908, 102 pp.

J. A. Bancroft. Geology of the Coast and Islands in British Columbia, Memoir 23, Canadian Geol. Survey, 1913, pp. 31–51, 119–123.

J. C. Branner. Stone Reefs, Bull. Geol. Soc. Amer., Vol. 16, 1905, pp. 1–12.

A. P. Brigham. The Fiords of Norway, Bull. Amer. Geog. Soc., Vol. 38, 1906, pp. 337–348.

H. M. Cadell. The Story of the Forth, Glasgow, 1913, 299 pp.

T. C. Chamberlin. The Attitude of the Eastern and Central Portions of the United States during the Glacial Period, Amer. Geol., Vol. 8, 1891, pp. 266–275.

G. H. Cook. On a Subsidence of the Land on the Seacoast of New Jersey and Long Island, Amer. Journ. Sci., 2d series, Vol. 24, 1857, pp. 341–355.

V. Cornish. Sea Beaches and Sand Banks, Geog. Journ., Vol. 11, 1898, pp. 528–543, 628–658.

R. A. Daly. Geology of the Northeast Coast of Labrador, Bull. Mus. Comp. Zoöl., Vol. 38, 1902, pp. 205–270; Pleistocene Glaciation and the Coral Reef Problem, Amer. Journ. Sci., Vol. 30, 1910, pp. 297–308.

J. D. Dana. Corals and Coral Islands, New York, 1872, 398 pp.

Charles Darwin. Structure and Distribution of Coral Reefs, London, 1842,

1874; Geological Observations, London, 1846; *ibid.*, 3d edition, New York, 1897.
C. A. Davis. Salt Marsh Formation near Boston and its Geological Significance, Econ. Geol., Vol. 5, 1910, pp. 623–639.
W. M. Davis. Dana's Confirmation of Darwin's Theory of Coral Reefs, Amer. Journ. Sci., Vol. 35, 1913, pp. 173–188; The Outline of Cape Cod, Geographical Essays, Boston, 1909, pp. 690–724; Der Marine Zyklus, Erklärende Beschreibung der Landformen, Leipzig, 1912, pp. 463–554; The Home Study of Coral Reefs, Bull. Amer. Geog. Soc., Vol. 46, 1914, pp. 561–577, 641–654.
J. W. Dawson. On a Modern Submerged Forest at Fort Laurence, Nova Scotia, Quart. Journ. Geol. Soc., Vol. 11, 1855, pp. 119–122.
H. W. Fairbanks. Oscillations of the Coast of California during the Pliocene and Pleistocene, Amer. Geol., Vol. 20, 1897, pp. 213–245.
N. M. Fenneman. Development of the Profile of Equilibrium of the Subaqueous Shore Terrace, Journ. Geol., Vol. 10, 1902, pp. 1–32.
G. de Geer. On Pleistocene Changes of Level in Eastern North America, Amer. Geol., Vol. 11, 1893, pp. 22–44.
A. Geikie. The Scenery of Scotland, London, 1887, pp. 46–89.
G. K. Gilbert. The Topographic Features of Lake Shores, 5th Ann. Rept., U. S. Geol. Survey, 1885, pp. 69–123; Lake Bonneville, *ibid.*, Monograph 1, 1890.
J. W. Goldthwait. The Abandoned Shore-lines of Eastern Wisconsin, Bull. 17, Wis. Geol. Survey, 1907, 134 pp.; The Twenty-foot Terrace and Sea-cliff of the Lower St. Lawrence, Amer. Journ. Sci., Vol. 32, 1911, pp. 291–317.
J. P. Goode. The Development of Commercial Ports, Chicago Harbor Commission, 1908, 103 pp.
J. W. Gregory. The Nature and Origin of Fiords, London, 1913, 542 pp.
F. P. Gulliver. Cuspate Forelands, Bull. Geol. Soc. Amer., Vol. 7, 1896, pp. 399–422; Shoreline Topography, Proc. Amer. Acad. Arts and Sci., Vol. 34, 1899, pp. 149–258; Nantucket Shorelines, Bull. Geol. Soc. Amer., Vol. 14, 1903, p. 555; Vol. 15, 1904, pp. 507–522; Vol. 20, 1910, p. 670.
F. G. Hahn. Inselstudien, Leipzig, 1883.
L. M. Haupt. A Menace to the New York Harbor Entrance, Bull. Amer. Geog. Soc., Vol. 37, 1905, pp. 65–77.
G. J. Hinde and Others. The Atoll of Funafuti, Report on the Materials of the Borings, Royal Society of London, 1904, 428 pp.
G. D. Hubbard. Fiords, Bull. Amer. Geog. Soc., Vol. 33, 1901, pp. 330–337, 401–408.
J. F. Hunter. Erosion and Sedimentation in Chesapeake Bay Around the Mouth of Choptank River, Prof. Paper 90–B, U. S. Geol. Survey, 1914, pp. 7–15.
D. W. Johnson. The Supposed Recent Subsidence of the Massachusetts and New Jersey Coasts, Science, N. S., Vol. 32, 1910, pp. 721–723; Fixité de la Côte Atlantique de l'Amerique du Nord, Annales de Géographie, Vol. 31, 1912, pp. 193–212; Beach Cusps, Bull. Geol. Soc. Amer., Vol. 21, 1910, pp. 599–624; Botanical Phenomena and the Problem of Recent Coastal Subsidence, Botanical Gazette, Vol. 56, 1913, pp. 449–468.
D. W. Johnson and W. G. Reed. The Form of Nantasket Beach, Journ. Geol., Vol. 18, 1910, pp. 162–189.
A. C. Lawson. The Post-Pliocene Diastrophism of the Coast of Southern California, Bull. Dept. Geol. Univ. Cal., Vol. 1, 1893, pp. 115–160; Geomorphogeny of the Coast of Northern California, *ibid.*, Vol. 1, 1894, pp. 241–272.
J. Le Conte. Tertiary and Post-Tertiary Changes of the Atlantic and Pacific Coasts, Bull. Geol. Soc. Amer., Vol. 2, 1891, pp. 323–330.
A. Lindenkohl. Submarine Channel of the Hudson River, Amer. Journ. Sci., 3d series, Vol. 41, 1891, pp. 489–499; *ibid.*, Vol. 29, 1885, pp. 475–480.

J. O. Martin. The Ontario Coast between Fairhaven and Sodus Bays, New York, Amer. Geol., Vol. 27, 1901, pp. 331–334.
Lawrence Martin. Some Features of Glaciers and Glaciation in College Fiord, Prince William Sound, Alaska, Zeitschrift für Gletscherkunde, Vol. 7, 1913, pp. 289–333.
J. Murray. Structure and Origin of Coral Reefs and Islands, Proc. Roy. Soc. Edinburgh, Vol. 10, 1880, pp. 505–518; Nature, Vol. 39, 1888, pp. 424–428; Vol. 40, 1889, p. 222.
F. Nansen. Oscillations of Shore Lines, Geog. Journ., Vol. 26, 1905, pp. 604–616.
O. P. Phillips. How the Mangrove Tree adds New Land to Florida, Journ. Geog., Vol. 2, 1903, pp. 10–21.
S. Powers. Floating Islands, Pop. Sci. Monthly, Vol. 79, 1911, pp. 303–307.
G. R. Putnam. Hidden Perils of the Deep, Nat. Geog. Mag., Vol. 20, 1909, pp. 832–837.
C. Reid. Coast Erosion, Geog. Journ., Vol. 28, 1906, pp. 487–495.
H. Reusch. Norges Relief, Norges Geologiske Undersogelse, No. 32, Aarborg for 1900, pp. 124–217, English summary, pp. 239–263.
G. B. Roorbach. Shoreline Changes in the Winthrop Area, Mass., Bull. Geog. Soc. Phila., Vol. 8, 1910, pp. 46–64.
W. Saville-Kent. The Great Barrier Reef of Australia, London, 1893, 387 pp.
E. C. Semple. Coast Peoples, Influences of Geographical Environment, New York, 1911, pp. 242–291.
N. S. Shaler. Postglacial Erosion of Martha's Vineyard, 7th Ann. Rept., U. S. Geol. Survey, 1888, pp. 347–351; Nantucket, Bull. 53, U. S. Geol. Survey, 1889, pp. 11–15, 47–52; Mt. Desert, 8th Ann. Rept., U. S. Geol. Survey, Part 2, 1889, pp. 1009–1034; Sea and Land, New York, 1894; The Geological History of Harbors, 13th Ann. Rept., U. S. Geol. Survey, Part 2, 1893, pp. 93–209; Evidences as to Change of Sea Level, Bull. Geol. Soc. Amer., Vol. 6, 1895, pp. 141–166; Beaches and Tidal Marshes of the Atlantic Coast, National Geographic Monographs, New York, 1896, pp. 137–168.
T. Sheppard. Changes on the East Coast of England within the Historical Period, Geog. Journ., Vol. 34, 1909, pp. 500–513.
W. J. Sollas. Funafuti, The Story of a Coral Atoll, Ann. Rept., Smithsonian Institution for 1898, pp. 389–406.
J. W. Spencer. The Submarine Great Canyon of the Hudson River, Amer. Journ. Sci., Vol. 169, 1905, pp. 1–15; *ibid.*, pp. 341–344.
Eduard Suess. The Face of the Earth, Part 3, The Sea, Vol. 2, London, 1906, 556 pp.
R. S. Tarr. Changes of Level in the Bermuda Islands, Amer. Geol., Vol. 19, 1897, pp. 293–303; Wave-formed Cuspate Forelands, Amer. Geol., Vol. 22, 1898, pp. 1–12; Chapter X, Physical Geography of New York State, New York, 1902; Postglacial and Interglacial (?) Changes of Level at Cape Ann, Mass., Bull. Mus. Comp. Zoöl., Vol. 42, 1903, pp. 181–191.
R. S. Tarr and Lawrence Martin. Recent Changes of Level in the Yakutat Bay Region, Alaska, Bull. Geol. Soc. Amer., Vol. 17, 1906, pp. 29–64; Geog. Journ., Vol. 28, 1906, pp. 30–43; Changes in Shorelines in 1899, Prof. Paper 69, U. S. Geol. Survey, 1912, pp. 18–32.
T. W. Vaughan. Geology of the Keys, Carnegie Institution, Year Book 8, 1909, pp. 140–144; Geologic History of the Floridian Plateau, *ibid.*, Publication 133, 1910, pp. 99–185; Physical Conditions under which Paleozoic Coral Reefs were Formed, Bull. Geol. Soc. Amer., Vol. 22, 1911, pp. 238–252.
T. L. Watson. Evidences of Recent Elevation of the Southern Coast of Baffin Land, Journ. Geol., Vol. 5, 1897, pp. 17–33.
E. Werth. Fjorde, Fjärde, und Föhrden, Zeitschrift für Gletscherkunde, Vol. 3, 1909, pp. 346–358.
W. H. Wheeler. The Sea Coast, New York, 1902, 78 pp.

A. W. G. Wilson. Cuspate Forelands along the Bay of Quinte, Journ. Geol., Vol. 12, 1904, pp. 106–132; Shoreline Studies on Lakes Ontario and Erie, Bull. Geol. Soc. Amer., Vol. 19, 1908, pp. 471–500.
J. E. Woodman. Shore Development in the Bras d'Or Lakes, Amer. Geol., Vol. 24, 1899, pp. 329–342.
J. B. Woodworth. Note on the Changes of Level of the Coast of Southern Chile, Bull. Mus. Comp. Zoöl., Vol. 56, 1912, pp. 116–132.

TOPOGRAPHIC MAPS

Bars shutting in Bays

Charlestown, R. I. — Duluth, Minn. — Pulaski, N. Y.
Martha's Vineyard, Mass. — Boston Bay, Mass. — Oswego, N. Y.

Beaches and Tied Islands

Coos Bay, Ore. — Boston Bay, Mass. — Cleveland and Vicinity, O.

Coral Reefs

U. S. Coast and Geodetic Survey charts, Nos. 15, 170, 1007. See also Joukin's *Cartes des bancs et récifs de coraux*, 4 sheets, Paris, 1912.

Drowned Coast

Boothbay, Me. — Coos Bay, Ore. — Seattle, Wash.
San Francisco, Cal. — New Haven, Conn. — Brooklyn, N. Y.
Charlestown, R. I. — New London, Conn. — Boston Bay, Mass.
Martha's Vineyard, Mass. — Stonington, Conn. — New York City Special

Drowned Coastal Plains

Leonardtown, Md. — Pt. Lookout, Md. — Choptank, Md.
Barnegat, N. J. — Sandy Hook, N. J. — Norfolk Special.

Drowned Lake Coast

Duluth, Minn. — Pulaski, N. Y. — Plattsburg, N. Y.
Oswego, N.Y. — Rochester Special

Harbours

Seattle, Wash. — San Francisco, Cal. — New Haven, Conn.
New York City Special — Duluth, Minn. — Norfolk Special

Lake Shores

Charts of the Great Lakes, U. S. Engineer's office, Detroit, Mich., or Buffalo, N. Y.; Maps 1, 5, 6, also Lake Ontario, Niagara River, Lake Erie, Lake St. Clair, etc.

Ocean Shores

U. S. Coast Survey charts, Nos. 6 (General Chart, coast of Maine and Massachusetts); 103, 104, 105, 106 (Maine coast, more detailed); 108 (coast from southern Maine to Cape Ann); 109 (Boston Bay); 8 (approaches to New York, Gay Head to Cape Henlopen); 113 (Narragansett Bay);

52 (Montauk Point to New York, with Long Island Sound); 119 (southern shore of Long Island); 121, 122, 123 (New Jersey coast, Sandy Hook to Cape May); 376 (Delaware and Chesapeake bays); 11 (Cape Hatteras to Cape Romain); 142 (Cape Hatteras); 147 (Cape Lookout); 188 (Mobile Bay); 19, 194 (Mississippi delta and vicinity); 21 (Galveston to the Rio Grande); 212 (bar from Rio Grande northward); 5400, 5500 (California coast); 3089, 8100 (fiorded Alaskan coast).

Offshore Bars, enclosing Lagoons

Atlantic City, N. J.	Barnegat, N. J.	Sandy Hook, N. J.

Sand Bars and Hooks

Brooklyn, N. Y.	Atlantic City, N. J.	New London, Conn.
Oceanside, Cal.	Martha's Vineyard, Mass.	Port Orford, Ore.
Plymouth, Mass.	Stonington, Conn.	Sandy Hook, N. J.

Wave-cut Cliffs and Islands

Port Washington, Wis.	Wellfleet, Mass.	Oswego, N. Y.

CHAPTER XII

MOVEMENTS OF THE EARTH'S CRUST, OR DIASTROPHISM

Changes in Level

Nature of Diastrophic Movements. — The instability of the relative level of land and sea has been frequently referred to in the preceding pages. In a great many cases this instability is the direct result of movements of the level of the sea itself. It is evident that a rise in the sea level will produce results similar to those due to a sinking of the land; and that the effects of lowering the sea level will resemble those of an uplift of the land. So close is the resemblance that it is not always possible to tell which of these processes has operated to produce a given change in relative position of land and sea.

Isostasy. — The causes for change in the level of the land are not well understood, and the consideration of them may, for the present, be deferred. It may be pointed out, however, that the crust of the earth is easily disturbed (*a*) by the operation of forces from within the earth, (*b*) by changes in load, a weighing down of the crust by deposit causing subsidence, a lightening of the crust by denudation causing a rising. At a given moment the earth form is in essential equilibrium, or isostatic adjustment, and if this equilibrium is disturbed, subterranean flow takes place to restore it, as would be the case in a liquid. The theory of *isostasy*, which teaches this mobility, seems now well established. Still a third possible cause for crustal movements is subterranean flowage to bring about adjustment to changing earth figure resulting from rotational variations.

Causes for Changes in Sea Level. — Changes in the sea level may result from (*a*) deepening of the ocean basins; (*b*) shallowing of ocean basins through deposit; (*c*) changes in the volume of water in the oceans; (*d*) variation in density or volume of the bordering crust, causing variation in gravitational attraction; (*e*) rotational variation. It is easily understood that a deepening of the ocean basins would withdraw water from the continent borders; that a shallowing of these basins would cause the sea to encroach on the land; and that an increase or decrease in the volume of the ocean water would bring about the same results. The ocean waters are held in place by gravity; and if gravitational attraction is locally increased or decreased, a local distortion of the sea level occurs. For example, the uplift of a great mountain chain, like the Andes, might produce a very decided distortion of the sea level by gravitational attraction; and the development of a great ice sheet, like those of North America and Europe, may affect the sea level not only by the withdrawal of much water, but also by exerting a lateral attraction upon the bordering sea. Variations in rotation, either in rate or in position of the axis of rotation, will cause a change in the sea level, since the oblate spheroid form will necessarily be adjusted to the changed conditions.

There are, therefore, a number of causes for change in relation of sea and land. Several of these causes have been in operation in bringing about the many changes that have occurred in the recent past, and that are still in progress; and it is not at all improbable that more than one process has been in operation in a single locality. The causes are so complex, and so little understood, that it is at present impossible to speak more definitely. Indeed it is quite common to speak of these changes as uplift or subsidence, as though the changes in level were all the result of actual crustal movement or *diastrophism.* In the use of these terms, however, it is tacitly understood that they do not necessarily mean to assert actual land movement, any more than the inherited term *sunset* asserts actual sun movement.

The change of level of the land in its relation to sea level may be either (*a*) upward or (*b*) downward, giving rise to either greater elevation of the land above the sea or to lowering of the land surface. These changes may be either (*a*) local, affecting only a slight area, or (*b*) general, affecting extensive areas; they may give rise to differential movement or to general change of fairly uniform character; and they may take place rapidly, or they may proceed with great slowness.

Evidences of Change of Level

There are many different kinds of evidence of a change in the relative level of land and sea, the greatest number and the best being those observed along the sea coast, for there even very slight changes are registered and easily detected.

Man's Observation of Emergence. — In some places actual human testimony proves uplift of the land, as in Yakutat Bay, Alaska, where the coast line was uplifted during the earthquakes of September, 1899 (Fig. 257). In still other cases human structures, such as piers or buildings, have been raised, as in Crete, where old docks now stand 27 feet above sea level. Upward movements have also been determined by actual measurement, as in northern Sweden, where marks placed on the coast for the purpose of testing the common belief that the level of the land was changing prove an uplift of 7 feet in 154 years.

Evidence from Elevated Shorelines. — Equally clear evidence of change in the relative level of land and sea is the presence of elevated shorelines, with wave-cut cliffs, sea caves, chasms, stacks, beaches (Fig.

258), and marine clays, — all the phenomena of shorelines excepting the presence of the ocean water. Such elevated shorelines, as already stated, are found back of many coasts, proving conclusively either that the sea level has been lowered, or the land level raised. It is a noteworthy fact that such shorelines are commonly tilted, and very often at such a sharp angle as to make it certain that it was the land that was raised, not the sea level that was lowered. Where the tilting of the shoreline is more gradual it is possible that the apparent uplift is the result of a deformation of the sea level itself, or it may equally well be due to a tilting of the earth's crust.

Evidence from Marine Organisms. — Another evidence of elevation of the land relative to the sea is the presence of remains of marine organisms in deposits on the land. Thus the finding of the skeleton of a whale in deposits in the Lake Champlain valley is accepted as proof that the sea once stood there; the presence in the deposits of the Texas coastal plain of marine shells of species now living in the Gulf of Mexico is proof that they were recently beneath sea level; and the presence of existing or recent species of marine organisms in hundreds of other places testifies to either uplift of the land or to a lowering of the sea level. Geological history records a complex succession of emergences and submergences of the land in all the continents; and it is as a result of these changes of level that we have so great a series of sedimentary rocks which were originally deposited in the ocean waters, now forming parts of the continents. Doubtless many of these changes are the result of variations in the ocean level; others are without doubt due to crustal movements.

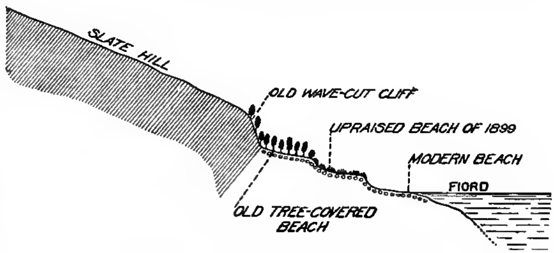


FIG. 257. — Beach uplifted in 1899, and older elevated beach, Yakutat Bay, Alaska.

Evidences of Submergence less Numerous. — As in the case of emergence there is human testimony of submergence also. Thus parts of the Yakutat Bay coast line sank during the earthquakes of September, 1899, while there was uplift in other portions; and in Crete, while there was uplift in one part, there has been sinking in another part, proved by the submergence of structures built by man. Since the sea covers the submerged land, the evidence of shorelines and marine fossils cannot be utilized to prove the change in this direction. It is, therefore, much less easy to discover evidence of submergence and very difficult to prove the exact amount.

Evidence from Stumps and Peat Beds. — Submergence is often indicated by the presence of tree trunks or stumps standing in place

Fig. 258. — Beach uplifted over 40 feet during earthquake in 1899 at Yakutat Bay, Alaska.

Fig. 259. — Barnacles and mussels attached to the rock on elevated shoreline, Yakutat Bay, Alaska.

at and below tide level, and by the presence of peat bogs beneath the salt water. Since such vegetation can grow only on the land, its presence below sea level is proof of a downward change of level of the land. The use of such evidence, however, is possible only when it can be demonstrated that there has not been local downsliding or local change in water level due to change in exposure to waves or tides (Fig. 260).

Evidence from Irregular Coasts. — One of the best evidences of land submergence is the drowned land topography of many coast lines, such as northeastern North America and northwestern Europe. Where the sea enters the land valleys, transforming them to bays,

Fig. 260. — Forest killed by submergence in Yakutat Bay earthquake of 1899.

harbours, estuaries, and straits, while the divide areas form peninsulas, capes, islands, and shoals, the evidence is fairly clear either that the land has subsided or the sea level has risen. The only important exceptions are where differential crustal movements have given rise to coastal irregularity, and where glaciers have eroded valley bottoms below sea level. The former are limited to a few sections, the latter to regions of powerful glacial scour where they form fiords. Elsewhere the cause for the irregularity is certainly a downward change in relative level of land to sea. Further proof of such a change has been revealed by soundings, which have discovered drowned river valleys, like the channel of the Hudson River on the sea bottom southeast of New York City (Fig. 116), and completely drowned valleys off the New England coast, off the mouth of the St. Lawrence, and in the North Sea.

Instances of Change of Level

Thousands of instances of recent or present day changes of level of the land are now known, and from among these only a few can be selected for specific treatment.

Yakutat Bay, Alaska. — During a series of several earthquakes in September, 1899, the coast line of Yakutat Bay, which pierces the St. Elias Range of Alaska, was greatly deformed. One part of the coast was uplifted 47 feet; other portions were raised less; there was no uplift along some sections of the coast; and in some parts there was actual depression (Fig. 261). In this case the change of level was certainly the result of diastrophism; the movements were local and differential; and they were abrupt, occurring certainly within a period of about three weeks, and possibly in a single day.

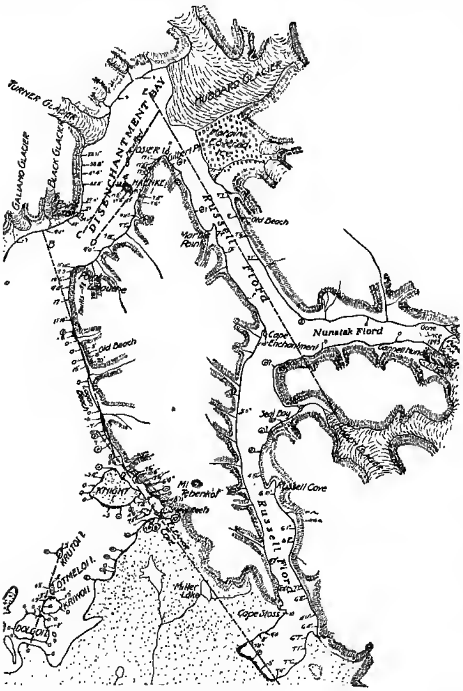


Fig. 261. — Map showing fault lines and amounts of uplift and depression during Yakutat Bay earthquake of 1899.

When studied in 1905, barnacles and mussel shells were still clinging to the uplifted shore (Fig. 259); and, in the area of depression, dead and dying trees were still standing in the salt water where they were lowered during the earthquakes. In the zones of uplift there were beaches so perfect in form that one could scarcely realize that the waves no longer reached them; but annual plants and young shrubs had begun to grow amid the barnacles and on the sand and pebble beaches where the waves beat a few years before. There were also wave-cut sea cliffs, chasms, sea caves and stacks; but at the new sea level there were no such shoreline features, because the waves had not yet had time to develop them.

Changes Associated with Growing Mountains. — The neighbouring region furnishes evidence of other earlier changes of level. The rocks near Pinnacle Pass, west of Yakutat Bay, at an elevation of

5000 feet above sea level, contain willow leaves and mussel shells of species still living in the adjacent ocean. This is the common condition in regions where mountains are still in process of growth. There are evidences of local, differential changes of level of the land along the California coast; for example, local subsidence admitting the sea across the Coast Range at San Francisco and giving rise to San Francisco Bay, and uplift on Santa Catalina Island, and along the coast south of Los Angeles; but the time of occurrence of these changes of level is not recorded. Similar differential movements have occurred in many parts of the Mediterranean, in New Zealand, in the West Indies, in Japan, and in many other parts of the world; and uplift associated with mountain growth has left clear records along the western base of the Andes.

It is certain that areas of subsidence are associated with many, if not all, mountain uplifts. The great depth of the sea near the West Indies is explicable only on this theory; and sinking of the ocean bottom off western South America seems necessary to account for the great depth of the ocean there. The floor of parts of the Mediterranean is evidently still sinking, for submarine cables are sometimes rent asunder during periods of slipping. Hidden from view, these submarine movements attract less attention than those of the land, though there is reason to believe that they are actually more important than the changes of level in that part of the crust that is exposed to direct observation.

Pozzuoli, on the Bay of Naples. — One of the most famous instances of change of level is that recorded by the ruins of the temple of Jupiter Serapis near Naples (Fig. 262). This temple was built before the Christian era, and then came a series of changes of level, as follows: (1) After the temple was built, subsidence occurred, so that a new pavement had to be built. (2) Following this subsidence of 5 feet came a period of rest and as late as the year 235 A.D. the temple was above sea level. (3) Then followed a slow subsidence of 12 feet during which the marble columns were encased in mud as they were lowered beneath the sea. (4) A further subsidence of 9 feet occurred so rapidly that the columns were not enclosed in sediment, and, therefore, the boring shell *lithodomus* was able to perforate the upper part of the limestone columns. (5) A period of rest followed, during which the lithodomus extensively perforated and roughened the limestone columns. (6) Then came uplift of 23 feet or more, bringing the columns above sea level, in which position they were found in 1749. (7) Subsequent to this there has been a slight subsidence. There is indication that sinking is still in progress, and careful measurements are now being made to determine the rate.

In this case there can be no doubt that most, if not all, the movements are really crustal changes; and they are probably in some way related to volcanic activity, for Pozzuoli lies between the volcanic Vesuvius and Ischia, and in the midst of a group of smaller cones.

Instability of the crust is common in volcanic regions, and numerous other illustrations could be given. Such changes of level, whether

FIG. 262. — The columns of the ruined temple of Jupiter Serapis at Pozzuoli, near Naples.

up or down, are doubtless related to migrations of molten rock beneath the crust.

Scandinavia. — In the time of Linnæus in the middle of the eighteenth century it was a matter of common belief that southern Sweden was slowly sinking, for rocks and reefs were reported to be gradually disappearing beneath the water, and streets, as at Malmo, were submerged. In the north of Sweden, on the other hand, the evidence pointed to uplift. This led Linnæus to start a series of records; and, by careful study of the evidence, it has been found that while the land has been rising north of Stockholm, having risen about 7 feet in 154 years, it has been sinking in the south. There is, however, evidence that this subsidence has now ceased.

Both in Sweden and Norway there have been still earlier changes of level. There was, for example, the great subsidence that gives the irregular coast line; then, after the Glacial Period, there has been an uplift, and the beaches, wave-cut cliffs, and marine clays are plainly to be seen, not at uniform level, but varying from point to point, and rising toward the fiord heads. Between these periods was one in which the land stood for a long time from 200 to 300 feet higher than now, and the wave-planed bench and the sea cliff of this stage are prominent features of the Norwegian coast. The bulk of the population of Norway dwells on the bench of this stage, or else on the marine clays of the last uplift.

It is noteworthy that the (1) great depression occurred during the stage of glaciation; (2) the great uplift occurred during interglacial time; (3) the last uplift succeeds the withdrawal of the ice. This has naturally led to the theory that the glaciation is responsible for these changes of level, (*a*) partly by actual depression as a result of the ice load on the crust, and subsequent rebound, still in progress, when the load was removed; (*b*) by the attraction of the ice mass distorting the sea level, which might explain part of the rise in the beaches up the fiords in which ice tongues lay as the glacier receded.

Other Northern Lands. — Subsidence during glaciation and subsequent uplift are also observed in many other regions of former glaciation. There are upraised sea beaches and associated sea cliffs from 20 to 25 feet above sea level along the western coast of Scotland; there is a series of well-preserved beaches in Spitzbergen, in Baffin Land, Labrador, eastern Canada, and Maine. The beaches of Spitzbergen, where extensive glaciers still remain, are not nearly so high as those of Labrador and Baffin Land, from which the ice has largely withdrawn. In Greenland, still the seat of a great ice sheet, subsidence is still in progress along some 600 miles of coast line.

Northeastern North America. — The irregular coast line of northeastern North America clearly proves a great submergence, more in the north than in the south; but in the south the submergence followed an emergence, and put beneath the sea only a portion of the previously upraised sea bottom. Whether these changes are due to crustal movements or to changes in sea level, or to a combination of the two, cannot at present be proved. That the land in the north was higher before the Glacial Period, and that it sank during that period, suggests a possible relation to glaciation. One great difficulty, however, is the fact that the level of preglacial time has not been even approximately restored; for although there has been an uplift varying from 5 or 10 feet near Boston to several hundred feet in Labrador, the land still lies far below its former level, and it does not seem to be still rising. In fact, the latest movement has been one of slight subsidence, for submerged peat beds and tree trunks are found at various points along the coast of New England and New Jersey. In the latter state there is apparently a subsidence at present in progress at the rate of about 2 feet per century, although this has been disputed. It seems probable, therefore, that, even though glaciation may be responsible for some of the changes of level, other causes, either for crustal movement or for change in sea level, are necessary to explain the phenomena.

In the Continent Interior. — Away from the sea coast changes of level, even of considerable amount, might occur without detection. Therefore there is little proof of such change as a result of direct observation. There are cases in which points visible from a certain locality are reported to have become invisible as a result of change of level at one of the points, or at an intervening point. There are also cases where lake waters have been tilted so far as to enter into and drown stream valleys that were formed before the tilting. This is well illustrated along the southern shores of the Great Lakes; for instance, at Chicago, where the lake waters enter and form a small harbour in the Chicago River; along the southern shore of Lake Ontario, where many stream valleys are drowned and transformed to bays and lagoons; and at the mouth of Niagara, where the lower course of a former period is now wholly beneath lake water.

A commonly accepted indication of change of level in the interior is the fact that the beaches and other shoreline phenomena of formerly expanded lakes are tilted. Thus the shorelines of the expanded Lake Iroquois, south of Lake Ontario, rise at the rate of about 5 feet per mile in a northeasterly direction; and the shorelines of former Lake Agassiz rise at the rate of 1.3 feet per mile. This apparent tilting of the land may, in part at least, be due to original tilting of the lake waters, attracted toward the ice dam which held them in. That it is not wholly due to this cause is indicated by the careful measurements made by Gilbert, as a result of which he concludes that there is at present in progress an uplift of about 9 inches a century at Toledo, 6 inches at Duluth, and 9 to 10 inches at Chicago, giving a tilting toward the northeast of about 5 inches per hundred miles in a century. Still earlier, Spencer had reached the conclusion that there was present uplift of about $1\frac{1}{4}$ feet per century in the Niagara River region.

The shorelines of former Lake Bonneville are also deformed (Figs. 218, 219, 254), and here the deformation is certainly in large measure the result of diastrophic movements, subsequent to the formation of the shorelines, for some parts of the shoreline are 350 feet higher than other parts (Fig. 263). In this mountain region changes in level are undoubtedly still going on in connection with mountain growth; and in other mountain regions similar changes are certainly in progress. Instances of this kind are given in the discussion of earthquakes.

Instability of the Earth's Crust

The instances of change of level given in the preceding paragraphs are only a few of the many that are established by complete evidence. There are no coast lines that do not furnish evidence of some change in the recent past; and there are probably few, if any, coast lines that are at present in a state of actual stability. Subsidence, elevation, or warping are common phenomena of coasts; and there is no reason for doubting that, if we had equally clear means of detecting changes away from the coast, the same statement could be made with regard to the interior of the continents and the ocean floor.

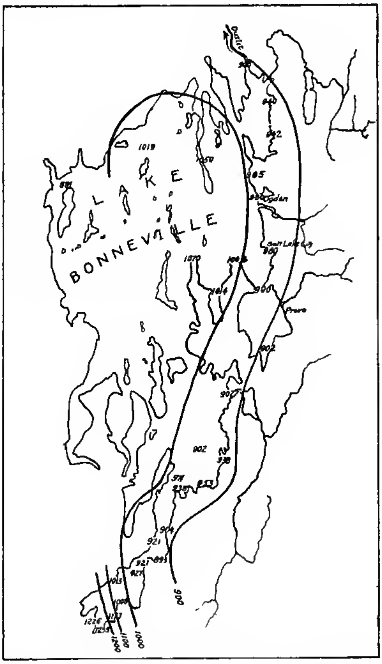


Fig. 263. — Map to show deformation of the shorelines of Lake Bonneville. Contours of 900 to 1200 feet pass through points of equal warping. (Gilbert.)

Some of these changes of level are rapid enough to be called paroxysmal; but the great majority are slow movements of the earth's crust, or of the sea level, or of both combined. These movements have been in progress throughout past time, and prodigious changes have taken place as a result of their continued operation. Thus sedimentary strata with marine fossils are found on plateaus thousands of feet above sea level, and among lofty mountains, 5000, 10,000, and even 15,000 feet above the sea. The movements of the past are continuing in the present; and there is every reason for believing that they will operate in the future.

The land is being attacked by denudation, and the fragments are being borne into the sea now, as throughout geological time. Were it not for the effect of diastrophism, by which elevation above sea level is being renewed here and there, the lands would long since have been lowered to a surface of low relief, standing but little above the level of the sea. There has, without doubt, been actual upward movement of the crust in places, downward movement in others, and warping elsewhere; and there has been distortion of the sea level, and rising and sinking of the surface of the ocean. As a result of these complex movements, changes in the relation of sea and land have been frequent and great in extent. It is not possible to assign exact value to each of the types of movement, nor, in some cases of change, to state the exact nature of the cause; but, speaking generally, the evidence indicates that the change in level through diastrophic movements of the crust is the most common, widespread, and effective.

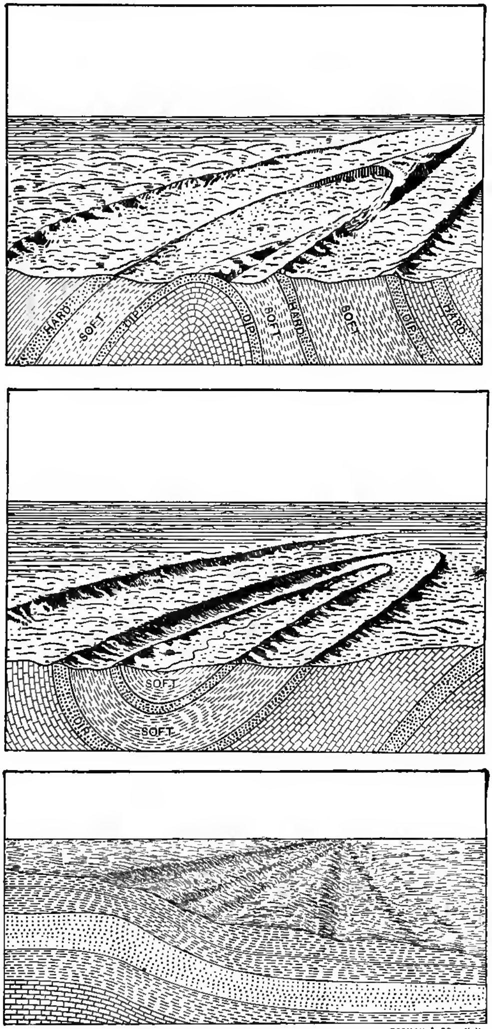
Disturbance of the Strata

Structures Produced by Earth Movements. — One of the most striking proofs of crustal deformation is the condition of the strata themselves. Not only are beds that were deposited in the sea now found in all the continents and even in the loftiest mountains and plateaus; but these strata, originally deposited in horizontal, or nearly horizontal, position are now found tilted at all angles. This tilting has been brought about (1) by folding, (2) by breaking or faulting, along certain planes. A third result of the diastrophic movements has been the development of a complex series of cracks known as joint planes.

Nature of Folding. — Subjected to the slow stresses which give rise to crustal deformation, even the brittle rocks yield by bending when weighted down by superincumbent layers. In many cases this is the result of mechanical gliding of grain on grain; but in rocks under heavy pressure there is actual flowage.

Anticlines and Synclines. — The simplest form of folding is that in which the strata are thrown into a somewhat symmetrical series of upfolds and downfolds, wave-like in their form (Fig. 264). The upfold, or arch, is an *anticline*, in which the strata incline, or *dip*, away from the central axis; the downfold, or trough, is a *syncline*, and here the layers dip toward the axis of the fold. Anticlines and synclines on the lands rarely stand out as topographic forms in their perfected state; for, like all land surfaces, they are subjected to denudation during and after formation. The inclined strata of which they are composed do, however, give rise to very striking topographic features, as is shown in the discussion of the denudation of mountains.

Forms of Folds. — Both anticlines and synclines may be either *symmetrical*, or *unsymmetrical*, in the latter case with one side steeper than the other. Very often one limb of an anticline is pushed over past the perpendicular, and it is then said to be *overturned*, or, if pushed over to a nearly horizontal position, *recumbent*. There is great complexity of folding among mountains, the strata sometimes being thrown into a series of folds, in which the layers, though greatly folded, are all inclined in a single direction, a condition known as *isoclinal* folding. There is also complex contortion and *crumpling*, as one might crumple sheets of paper (Fig. 265). When exposed to denudation, all these varieties of rock position give rise to appropriate influence on topographic form.



BORMAY & CO., N.Y.

Fig. 264. — Anticline, above; Syncline, middle; and Monocline, below. The first two greatly modified by erosion. (After Willis.)

In a region of mountain folding the rocks are thus thrown into a complex system of folds, each individual fold having a linear extension along an axis, but dying out in both directions. The strata, therefore, not only dip on either side of the axis, but they have an inclination along the axis, known as the *pitch* of the fold. The direction of the axis of a fold is the *strike*. Anticlines and synclines may be long and narrow, or short and broad, and the pitch may be either steep or gentle. The folded layers of a symmetrical syncline of medium length, breadth, and pitch often has the form of a canoe; and a similar anticline the form of an inverted canoe.

Geosynclines and Geanticlines. — Some areas of the earth's crust subside for a long period of time, as was the case in the western Appalachian Mountains before these mountains were uplifted, and for such areas Dana proposed the term *geosyncline* or earth syncline. The Appalachian geosyncline was a trough of depression through several geological ages before uplift took place, and during this subsidence over 25,000 feet of strata were laid down, later to rise in a series of mountain folds. The opposite condition of long-continued rising is a *geanticline.*

In a much folded series of strata there are groups of folds, roughly parallel. If such a group is in general anticlinal, though including both anticlines and synclines, it is called an *anticlinorium;* if synclinal, it is called a *synclinorium.*

Domes and Monoclines. — In some parts of the earth the strata are raised in *domes*, as where lava has been thrust into the crust, lift-

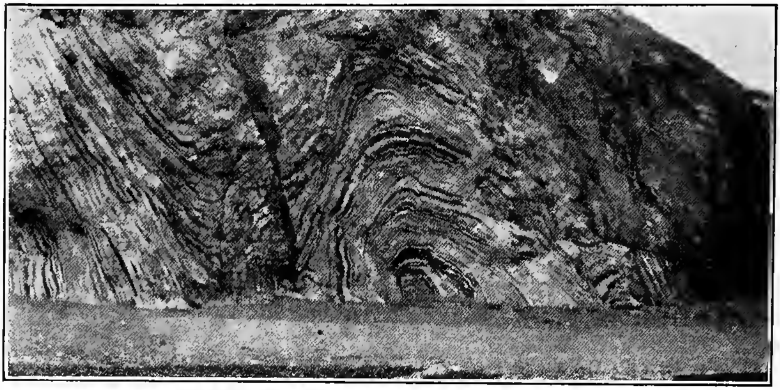


Fig. 265. — Anticline, syncline, crumpled or contorted strata, faults, and an igneous dike in southwestern Alaska. (Stanton, U. S. Geol. Survey.)

ing the rocks above. In such cases the strata dip in all directions from the centre of the dome. Another type of fold is the *monocline*, in which there is a single sharp bend (Fig. 264), as is common in the plateau country of southwestern United States, where the horizontal strata are interrupted by an abrupt dip, then the horizontal position is resumed. Monocline folds are commonly associated with faulting, and often merge into faults.

Relation of Folds to Topography. — All these types of folding are definite proof of diastrophism, for the rocks of the crust have clearly been deformed as a result of stresses applied in crustal movements. They cause notable effects on the topography, first by the general upward or downward movements, as a result of which elevations and depressions of portions of the surface are caused, and, secondly, by inclining at various angles rock strata differing in character and in degree of resistance to the agents of denudation which are engaged in the task of reducing the elevations.

Nature of Faulting. — When the strain in diastrophic movements is applied too rapidly, or in too brittle rocks, or in strata not heavily enough weighted by superincumbent load, breaking, instead of folding, will result. This breaking is naturally more apt to be common at or near the surface than at considerable depths below the surface; and it is very probable that superficial breaking commonly grades downward into folding. In a given rock a strain slowly applied may cause folding, while the same strain rapidly applied causes breaking; a given strain, applied at a given rate, may cause folding in one stratum and breaking in another; and a given strain, in a given rock applied at the same rate, may cause breaking under the atmospheric pressure, and folding under the pressure of a thousand feet of strata.

Fault Planes. — The breaks produced by stresses during crustal deformation are known as *faults*, and the plane along which the slipping occurs is the *fault plane* (Fig. 266). The fault plane may lie vertically, or at any angle from this to horizontal, and the movement along the fault plane may be vertical, or horizontal, or diagonal. There may be movement on both sides of the fault plane, or on only one side. Ordinarily there is a vertical element in the movement along a fault plane so that one side is left higher than the other. The higher side is called the *upthrown* side, the lower side the *downthrown;* but this does not mean that one side has been thrown up and the other down, for either a downward movement on one side of the fault plane, or an upward movement on the other side, will give the same result. The fault plane may be a single break, though more commonly there are numerous parallel breaks close together, and the rock along the fault plane is often crushed and broken, giving rise to a *fault breccia.* As the moving rock grinds together, the walls are commonly polished and grooved, giving the appearance called *slickensides.*

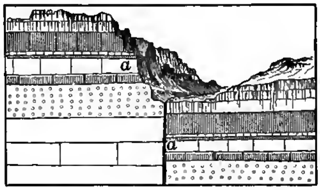


Fig. 266. — A fault plane with the same layer, *aa*, standing at different levels. (Powell.)

Step Faults and Graben. — There is great variety in faulting, according to the angle of inclination, or *hade*, of the fault plane, and to the position of the strata crossed by the fault plane. There are parallel faults, or *step faults* (Fig. 267), giving rise to steps in the strata that are raised or lowered by faulting; there are parallel faults between which a block of the earth's crust has settled, forming a *graben* or trough fault (Fig. 268); and there are single faults. The latter may cross either horizontal or inclined strata, and in the latter case they may be parallel to the dip or may cross it at various angles.

Normal Faults. — A large number of faults, called *normal*, or *gravity* faults (Fig. 269), have the fault plane inclined, or hading, toward the downthrown side. In such a fault the dislocated strata are separated by movement along the fault plane, so that there is not only a vertical

FIG. 267. — Step faults near Nunatak Glacier, made during Yakutat Bay earthquake of 1899.

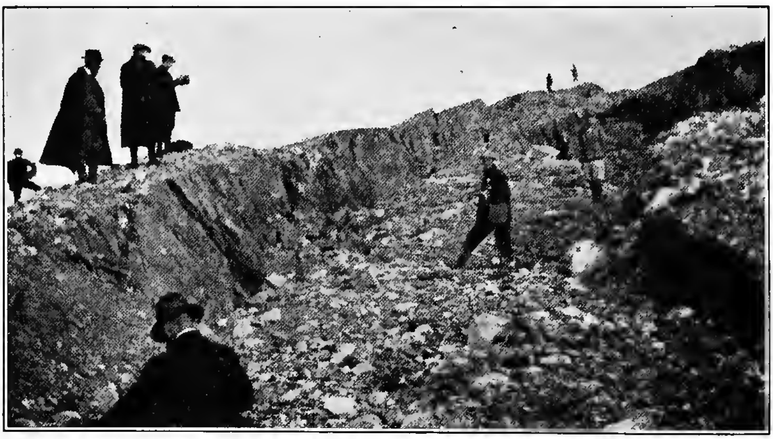


FIG. 268. — Rift or graben fault near Nunatak Glacier, Alaska. Photographed 14 years after the faulting took place. (Hatch.)

displacement or *throw*, but also a horizontal displacement, or *heave*, leaving the ends of the dislocated strata apart. In a normal fault a vertical line dropped from the end of a layer on the upthrown side will be separated from the end of the same stratum on the downthrown side by a certain horizontal distance.

Overthrust Faults. — The opposite type of fault is the *reversed* fault, in which layers are thrust over one another. In this case a vertical line dropped from the end of a layer on the upthrown side will pass through the same layer on the downthrown side. In reversed faults the angle of hade is often so great that the fault plane approaches the horizontal, and the layers are thrust over one another along these

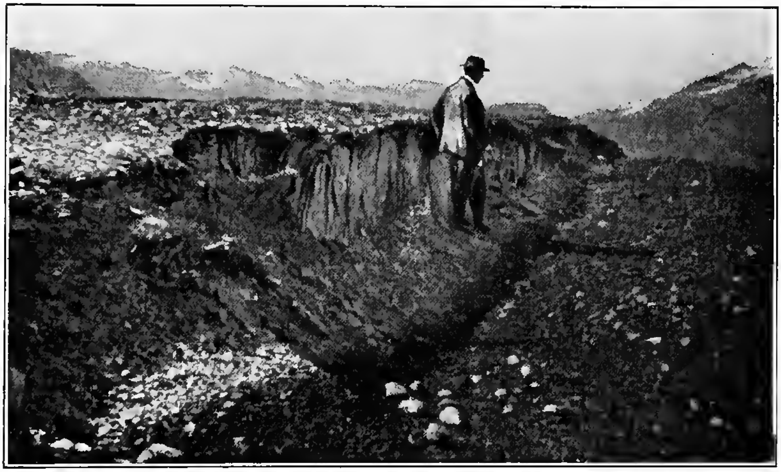


Fig. 269. — Normal fault with throw of over 3½ feet, made during Yakutat Bay earthquake of 1899. Photographed 6 years after faulting took place. After 8 years more this fault was much more obscured by talus.

planes of low inclination. Such a fault is an *overthrust* fault, common among many mountain regions, where older strata are sometimes thrust forward over younger for a mile or more. In an extreme case, as in the Rocky Mountains of Glacier National Park, the overthrust may be 7 to 12 miles. Such thrust faulting is now known to be a normal feature of many mountains, like the Alps, the Scottish Highlands, and Scandinavia (Chap. XV). It proves great crustal movements accompanying mountain deformation and great horizontal transfer of upper layers of the crust.

Horizontal Movements along Faults. — Movements along vertical and highly inclined fault planes may also involve horizontal transfer of portions of the crust, as was the case during the California earthquake of 1906, when the surface on one side of the fault plane 300 miles in length was shifted horizontally from 8 to 20 feet (Fig. 270).

More commonly the surface is raised or lowered by either upward or downward movement on one side of the fault plane. Such movements are actually observed during the earthquakes; and, after the movement is over, the surface is left permanently higher on one side of the fault plane than on the other. In the Japanese earthquake of 1891 both movements were observed in connection with a fault plane 40 miles long, on one side of which the surface sank from 2 to 20 feet, while there was a lateral shift of 13 feet in places. (Fig. 282.)

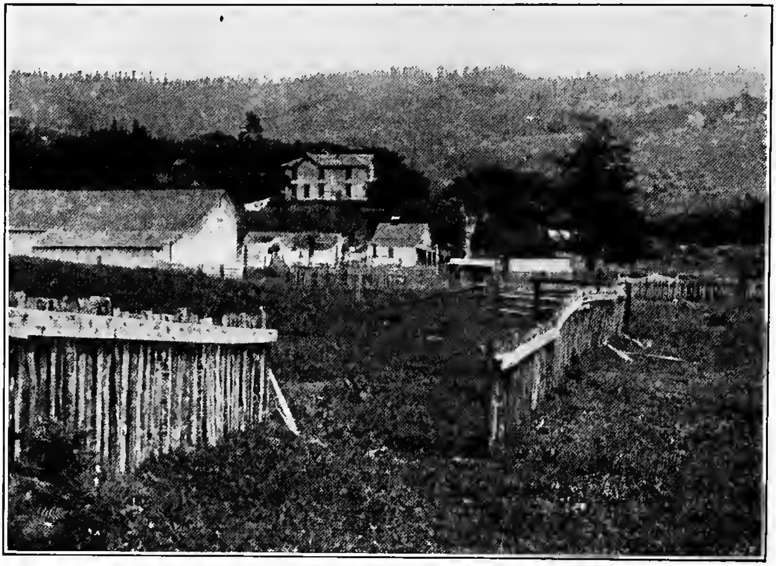


FIG. 270. — Horizontal movement along fault line in California. Before the earthquake of 1906 the two parts of the fence in the foreground were continuous and in the same straight line. (Gilbert, U. S. Geol. Survey.)

Great Faulting accomplished Slowly. — Evidence of movements accompanying faulting is furnished by geological study of strata in all parts of the lands, but especially in mountain regions, the throw in some cases amounting to thousands of feet. It is not to be inferred that such movements occurred in a brief period of time, but rather that, as the stresses were applied, successive slippings occurred until in the course of long periods of time a great total throw was attained. Doubtless the faults in which present-day movements are observed give a clear indication of the nature of the movements by which the great faults of past ages were formed.

Fault Scarps, Rift Valleys, and Horsts. — Faulting produces a direct effect on topography by forming a cliff, or *fault scarp*, on one side of the fault plane. Such fault scarps are often developed during earthquakes, as in Japan in 1891 and in Alaska in 1899. If the movement continues, the scarp may rise higher and higher, giving rise to a pronounced cliff, of which there are many instances in mountains and plateaus of recent uplift, as in the Basin Ranges of the Great Basin and in the Colorado Plateau. Davis has emphasized the contrast between fault scarps, due to diastrophic movement by faulting, and *fault-line scarps*, due to erosion of a faulted structure. Fault scarps may even be completely obliterated by erosion, whose continued action later produces a fault-line scarp facing in the opposite direction (Fig. 271).

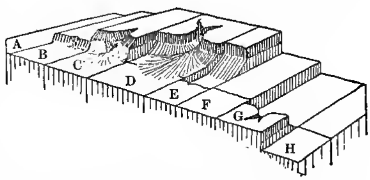


FIG. 271. — Fault scarp BC, obliterated by erosion F, fault-line scarp G. (Davis.)

Linear depressions known as *rift* or *graben valleys* may also be formed by diastrophism as in the Coast Ranges of California, the Dead Sea valley and elsewhere. The sinking of great blocks of the crust between fault planes gives rise to a large *graben*, like the Lowlands of Scotland, and the broad valley of the upper Rhine. It has been shown that the Lake Superior basin is a graben (Fig. 272), at least its western portion, due either to recent faulting, or, more probably,

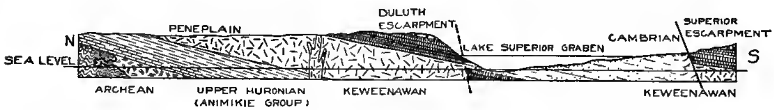


FIG. 272. — The rift valley or graben of western Lake Superior.

to ancient faults whose escarpments have been buried beneath sedimentary strata and resurrected by later denudation. Even the Mediterranean depression is explained as the result of the subsidence of a portion of the crust between a series of fault planes; and similar subsidences are doubtless also in progress in parts of the ocean bottom, in intermontane valleys on the land, and along the fronts of growing mountains. Portions of the sea bottom may be raised to form peninsulas or islands, and coast lines may be raised above the sea, as occurred in the Yakutat Bay region of Alaska in 1899. Upfaulted blocks are called *horsts* (Fig. 273). They may also be due to downfaulting on both sides of a stationary block of the earth's crust.

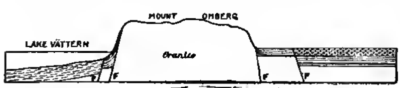


FIG. 273. — A horst in southern Sweden. (de Geer.)

Relation of Faulting to Topography. — Indirectly faulting is also important in modifying topography. In some places the fault plane serves as a guide to drainage, especially where a series of parallel or branching faults so crush the rock as to render it weak; but the guidance of streams by this cause is much less important than was at one time thought, for the fault is usually only a narrow break, and is a much less efficient cause for influencing stream erosion than other causes, such as variation in strata. In fact, streams very often cross great fault planes, or flow parallel to them without actually coinciding with them.

One very important influence of faulting is the placing of strata of varying degrees of resistance within the reach of the agents of denudation. They are then attacked and worn away irregularly. Thus a fault scarp wastes away as it rises, and when movement ceases it is given over wholly to the attack of the agents of denudation. The cliff recedes from the fault plane, and its form varies with the influence of the component strata, so that ultimately it may be far removed

FIG. 274. — Joint planes near Ithaca, N.Y.

from the fault plane with which it was originally associated. It may, indeed, be worn down to such low relief as to lose all resemblance to a fault scarp, and the position of the fault plane be recognizable only after careful geological study of the strata. Many fault planes find no surface expression in the topography; and others are indicated in the topography only by the differences in form of the land, caused by the influence of the strata on the two sides of the fault plane as etched out by denudation.

Nature of Joint Planes. — The cooling of lava rocks, causing contraction, gives rise to internal strains in the rocks as a result of which breaking occurs along planes called *joint planes*. Drying of sediments also causes contraction and jointing (Fig. 274). But much more important than either of these causes for joint planes is the introduction of strains, either of tension or compression, as a result of which the rock breaks along a series of planes. Such joint planes are developed in all classes of rock, and they give rise to natural breaks, often of great regularity and definiteness of direction, as a result of which the rock is traversed by planes which divide it into rectangular or rhombic blocks. These planes may be far apart or near together, according to the nature of the rock and the intensity of the strain, sometimes traversing the rock so close together that it is broken into a multitude of small blocks a few inches in area.

Joint planes do not necessarily signify any visible motion, such as occurs along fault planes; but there is good evidence that there is sometimes actual motion along the joint planes. Associated with jointing, either during its formation or subsequently, there is often a crushing, and in much jointed rocks there are frequently broken, or brecciated, areas or zones.

Relation of Joints to Erosion. — All these forms of breaking are highly important in guiding the work of the agents of denudation, as we have seen. The joint planes offer paths for the entrance of percolating waters; they are seats of solution, chemical change, and frost action; they aid in the plucking action of glacial erosion, in the tearing out of blocks by wave attack, and in the erosive work of streams. Very often the topographic detail of coast line or gorge wall is joint-determined; and everywhere joint planes are guiding and aiding in denudation. Joint planes are one of the most important single factors of rock structure in influencing the shaping of the earth's surface under the agencies of denudation; and we may be certain that, without such influence, the land would waste away much less rapidly, and the surface features would be far different.

Earthquakes

Nature of Earthquakes. — Delicate instruments, known as *seismographs*, reveal the fact that tremors, not detected by the senses, are of common occurrence; and it is a well-known fact that more vigorous shaking, known as earthquakes, occurs every now and then, at times attaining such force as to cause great destruction of both property and life. It is probable that no moment passes without some tremor or quake occurring in some part of the earth. They originate in all parts of the earth, both on the land and on the sea bottom, but they occur far more commonly in some parts of the earth than in others; there are, indeed, well-defined earthquake belts in which by far the greatest number of shocks, and practically all the violent ones, occur.

Causes of Earthquakes

Small Shocks in Relation to Man's Activities. — Any jar that arises within the earth or on its surface is a cause for an earthquake, using the term in its largest sense and including even the most minute tremors. Thus the rumble of a heavily loaded cart over a paved street starts a series of tremors that may be measured by a seismograph near by, and which may be even detected by the senses. An explosion sets in motion more vigorous earth waves, as was the case with the great explosion at Hell Gate some years ago, when a small earthquake was artificially generated, which was measured on the instruments at Cambridge, Massachusetts, nearly 200 miles distant.

Other Causes of Minor Earthquakes. — The descent of an avalanche, or the falling of a mass of rock from a sea cliff will also cause a small earthquake. For example, the people of Niagara Falls are often made aware of the fall of a piece of limestone from the crest of the cataract by a trembling of the ground. Another cause for earthquakes is the falling of a portion of a cavern roof, a cause observed in England; and another is the snapping of rocks under strain. The latter cause is illustrated in the granite quarries of Monson, Mass., where, when the rock is stripped off, and pressure thus removed, strain in the layers finds relief by snapping, sending an earthquake tremor through the quarry. Doubtless this cause is in common operation in regions of denudation where, by the removal of overlying load, relief from strain becomes possible by bending and breaking of the layers on which the load hitherto rested. Subterranean movements of imprisoned gases or liquids, and change in temperature of the rocks or the ground are other causes for earth tremors.

Two Classes of Great Earthquakes. — These and other causes are, without doubt, operating to cause small earthquakes; but the great majority of earthquakes, and all or nearly all of the really destructive ones, are due to causes associated either with diastrophism or vulcanism. Those due to diastrophism are called *tectonic*, those due to vulcanism may be called *volcanic* shocks.

Tectonic Shocks. — Tectonic shocks are the direct result of movements associated with crustal deformation. When slipping occurs along a fault plane, there is a disturbance of the earth (1) by friction along the fault plane, (2) by breaking and crushing of the rocks, and (3) by the movement of the upraised or down-sunken layers. There is reason for believing that in great movements along fault planes there is also transfer of deep-seated rock by a process analogous to flowage. A tectonic shock may be only a minute tremor, generated by a slipping of minute extent; or it may be a movement involving many cubic miles of crustal layers, and giving rise to such disturbance that the earth near by is violently shaken, while waves sweep outward and completely encircle the earth so that the occurrence of a violent earthquake is recorded on the seismographs of the antipodes. Such great tectonic shocks consist of a complex series of waves generated by the slipping and breaking along the fault plane, and the bodily movement of great masses of rock. The plane along which the slipping occurs may extend for scores or even hundreds of miles; and the depth of the movement may reach thousands of feet into the earth. Tectonic shocks are the greatest of earthquakes, and the largest are truly world-shaking, though perhaps not noticeable to the senses except within a few hundred miles of the centre of origin. Tectonic shocks are also the most common of earthquakes, for the strains of crustal deformation are widespread, both on the lands and on the sea bottoms. They naturally occur most abundantly and with most vigour in belts of growing mountains, for there the strains of crustal deformation are most concentrated.

Volcanic Shocks. — Volcanic shocks are also common, and abound on and near volcanoes either at present active, dormant, or recently extinct. They result (1) from the explosion of an active volcano, (2) from the subterranean movements of lava, seeking escape. Volcanoes that have been reduced by denudation often reveal the presence of fissures filled with solidified lava, known as *dikes*. When these fissures opened it is possible that the earth was shaken in the neighbourhood, and the inward rush of the molten lava must also have caused a disturbance in the rocks round about. Earthquakes are common in the neighbourhood of volcanoes before an outbreak, and these are doubtless due to the intrusion of dikes and other movements of molten rock. When the final outburst occurs, there may be a great and violent earthquake in the region about the volcano, as was the case in the great eruption of Krakatoa in the Straits of Sunda in 1883.

Violent though such earthquakes sometimes are in the immediate neighbourhood of the volcano, they are not in the same class with the great tectonic shocks, for there is less material involved in the movement, and the area of disturbance is more limited. The volcanic shock is caused by movements within a limited area around and beneath the volcanic vent; the tectonic shocks may involve movements along a linear belt scores or hundreds of miles in length, probably extending as deep, if not deeper, than the volcanic movements. It is not meant to intimate that great destruction may not occur at or near the centre of a violent volcanic earthquake; but merely that the area of violent shaking is more limited, and the world-shaking character is less noticeable in the great volcanic than in the great tectonic shocks.

Nature of the Earthquake Shaking

The Focus and Epicentrum. — The nature of the movements in an earthquake shock will most easily be understood if we consider the impulse to start from a point, or from a single small area, as is undoubtedly the case in many earthquakes, notably the volcanic and minor tremors. A jar applied to such a point generates a series of elastic waves, which spread outward in all directions from the centre, or *focus*, as a series of waves will pass through a stone which is struck a blow with the hammer. If the medium through which the waves pass is assumed to be uniform, these waves will spread with equal rapidity in all directions, but will gradually lose in intensity equally in all directions from the centre of disturbance. Therefore the nearer the focus the sooner the shock is felt and the greater its violence.

Passing through the earth, the waves will in time rise to the surface, reaching it first and with greatest violence directly above the focus. This point is called the *epicentrum.* The origins of earthquakes are often very deep below the surface, the depth of focus of the Calabrian earthquake of 1857 being estimated as 5 miles and others being calculated at depths up to 14 miles.

Coseismals and Isoseismals. — The shock diminishes in violence in all directions and the time of appearance of the waves becomes later and later with increasing distance from the epicentrum. A series of lines connecting places at which the shaking appears at the same time are called *coseismals*, and lines passing through places of equal intensity of shaking are called *isoseismals.* The isoseismal lines are often roughly circular and concentric around the epicentrum.

Complexity of Earthquake Movement. — As a matter of fact the phenomena of the transmission of earthquake waves is far less simple than this assumed case, especially in the great earthquakes originating as tectonic shocks. Instead of a single wave or related series of waves generated from a single point, there may be a multitude of waves of varying strength, generated from many points and planes within the epicentral area, which may extend scores of miles, and reach thousands of feet into the earth. These waves, with different amplitudes, and from different centres, pass through strata of different kinds. Thus there is, in reality, a complex of waves. In a great earthquake the ground may be shaken for several minutes, with a violence varying as the different waves reach it, and at times reaching such strength that a person is thrown to the ground, and strong buildings are rent asunder. One shock may succeed another at intervals of several minutes, or hours, or days, as further motion takes place along the fault plane, or as adjustments occur in the disturbed strata. There is perhaps no natural phenomenon to which man is subjected that is more terrifying than a violent earthquake, and even wild beasts are subdued by terror during such a convulsion of the normally stable earth.

Destructive Effects

Changes in the Earth's Surface. — During the passage of the waves of a violent earthquake the ground is so shaken that unstable objects may be overthrown. Thus trees are overturned and avalanches are caused, sometimes forming temporary lakes. Loose earth is shaken down, and depressions and elevations are introduced in the loose soil. Fissures open and close, water is squeezed out of the ground, springs have their supply cut off, and even stream flow is interfered with, so that brooks dry up and later resume their flow. The water in lakes may rise and fall for several hours, even far from the shock.

With the disturbance of underground water, there is often an eruption of sand from *craterlets* or sand vents on the surface. Leading up to these are cracks filled with sand, known as *sandstone dikes*. Along the fault plane the surface may be permanently raised or lowered on one side; but this is an accompanying phenomenon, not a result of the earthquake; it is a surface expression of the movement by which the earth shaking is generated.

Destruction of Buildings. — Where the epicentrum or fault line passes through a settled country, there is introduced the great danger of falling buildings and subsequent fire, as a result of which vast destruction of life and property have been brought about. This danger decreases rapidly with distance from the source of the shock; it also varies with the nature of the underlying rock. Made ground and loose, unconsolidated strata are far less secure than solid rock, for, added to the direct shaking due to the earthquake waves, is the settling and movement and fissuring of the unstable foundation. Even the strongest building may succumb to the combined shaking and undermining of an unstable foundation.

There is much difference in the effect of earthquakes according to the construction of the building. Old houses of massive construction, with heavy floors and roofs, undoubtedly led to a large part of the terrible destruction during the Messina earthquake of 1908; and in San Francisco there was noticeable difference in destructiveness of the 1906 earthquake, not only in relation to stability of foundation, but also according to the construction (Fig. 275). The Japanese, living in an earthquake country, have given careful study to the subject of earthquake-proof buildings, and their light, low, bamboo houses are able to resist all but the most severe shocks. In Italy, too, thought is now given to construction of earthquake-resisting structures in the Calabrian region of the southern part of the peninsula, which has been visited by a succession of earthquakes of great destructiveness.

Perilous Location of Towns. — Attention ought also to be paid to the question of location of towns in earthquake countries. There are towns and even cities built on or close by fault lines, along which movements are known to have occurred, and where it is practically certain that other movements will take place. With the present knowledge of earthquake cause it is certainly folly to tempt fate by rebuilding on a fault line a town that has been destroyed by an earthquake generated through movement along such a fault. In Italy some village sites have been abandoned by government order since the Messina earthquake of 1908.

Seismographic Records

Movement of Earth Waves. — The establishment of stations in which seismographs are kept in various parts of the earth is adding greatly to our knowledge, not only of the distribution of earthquakes, but of the condition of the earth's interior. The seismograph is so made as to magnify and automatically record any vibration that passes through the earth on which it rests. It is found that the waves of a great earthquake (Fig. 276) pass around the earth, in both direc-

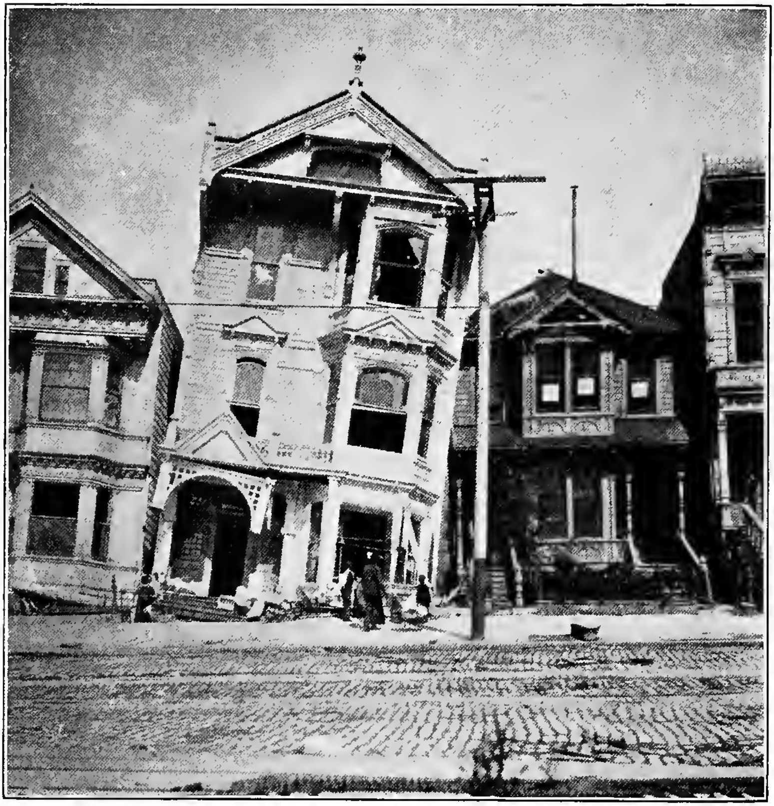


FIG. 275. — Dwellings displaced during the San Francisco earthquake of 1906. Not being adapted to standing the shock the three-story house lurched off its foundation, while those to the right were unharmed. (Gilbert, U. S. Geol. Survey.)

tions, and may even make a second circuit, travelling with a velocity of a little over two miles a second. Other waves travel through the earth at the rate of $6\frac{1}{4}$ miles per second, so that they are able to pass through the earth along one of its diameters in about 20 minutes. From their rate of travel and the uniformity of the velocity it is inferred that the earth's interior is of somewhat uniform composition and is one and a half times as rigid as steel.

The upward motion of a particle in an earthquake wave may be as little as 5 or 6 millimeters, or less, though with even this slight motion chimneys will be thrown down.

Location of Epicentra. — The seismograph records many earthquakes that would otherwise be unknown, such as those occurring in unsettled regions or on the sea floor. It records the intensity and duration, and from the records of three or more stations it is possible to determine both the position of the earthquake and the time of its occurrence. Thus it is now frequently stated that a vigorous earth-

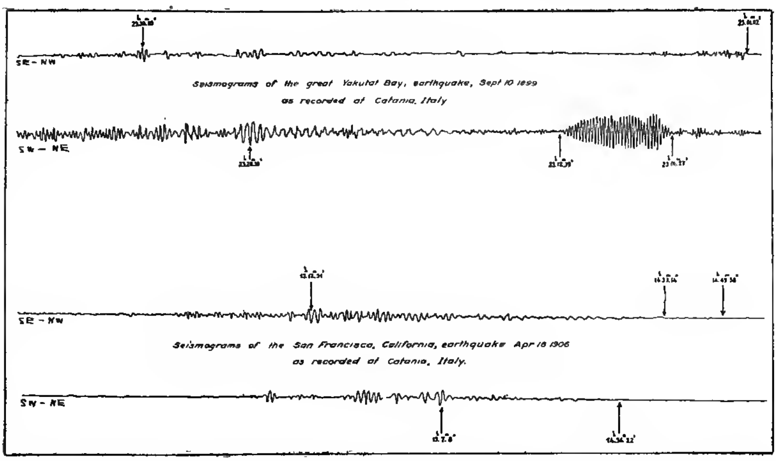


FIG. 276. — Seismograph records from an instrument at Catania, Italy, showing the records of vibrations of the earth's crust after the Yakutat Bay earthquake of 1899 and the California earthquake of 1906.

quake occurred at a certain time and place, perhaps even before the world has been notified of its occurrence by telegraph.

DISTRIBUTION OF EARTHQUAKES

Scores of Earthquakes Daily. — It is estimated that there are 30,000 earthquakes every year that are recognizable by the senses. Most of these are very light, and only a few are of the first order; but every year there are some shocks of great violence, and now and then one of these occurs in a settled region where sufficient destruction is accomplished to attract world-wide attention. It does not follow, however, that such shocks are the most violent; for their notoriety may be due rather to the accident of location than to exceptional vigour. Every year great earthquakes pass unheeded by all but seismologists because they happen to occur where no human life could be lost.

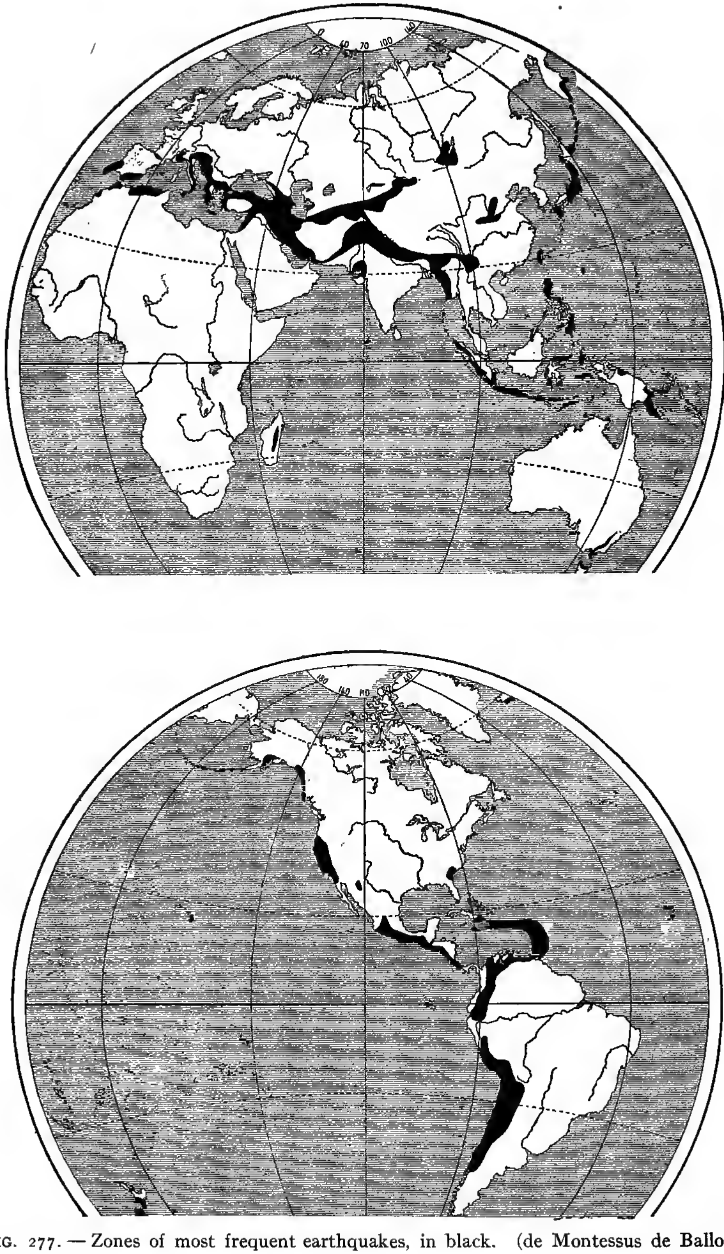


FIG. 277. — Zones of most frequent earthquakes, in black. (de Montessus de Ballore.)

The Two Belts of Earthquakes. — While earthquakes of minor intensity may occur in any place, the great majority of recorded shocks occur in two well-defined belts, or great circle zones. A few areas of frequent earthquakes lie outside these belts, and occasional great earthquakes have occurred in these outside areas. These facts have long been recognized in a general way, but it remained for Count de Montessus de Ballore to give it numerical proof on the basis of the great series of earthquake records that have been accumulated. He has studied and tabulated the records of no less than 170,000 earthquake shocks, and on the basis of these studies has put out the two maps reproduced here as Fig. 277. From these maps it is clear that there is one belt of abundant earthquakes encircling the Pacific, and another in a great circle approximately east and west around the earth, through the Mediterranean, southern Asia, the East Indies, and the West Indies.

Most Shocks within these Belts. — De Montessus finds that 41.05 per cent of all recorded shocks occur in the circum-Pacific belt, while 53.54 per cent occur in the other belt. Thus 94.59 per cent of 170,000 earthquakes studied occurred in these two belts, forming but a small part of the earth's surface; and only 5.41 per cent occurred in all the rest of the earth. Doubtless future study will cause some modification of this conclusion, now that seismographic records reveal to us the location of submarine earthquakes and tell us of earthquakes in uninhabited parts of the lands. For example, it is certain that a future map will assign greater seismicity to Alaska than de Montessus has given it on the basis of existing records; and seismic regions will without doubt be added in the oceanic areas. But it is equally certain that future maps will bring out with similar clearness the two great earthquake belts which he has demonstrated; and that they will show the greater part of the earth to be relatively immune to earthquakes of vigorous character.

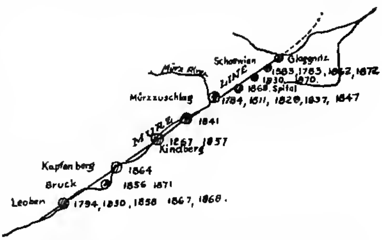


FIG. 278. — The Mürz line, which passes through places of repeated earthquakes in the years listed. (Suess.)

Relation to Mountain-making and Vulcanism. — The reason for these two belts is not difficult to see. These are belts in which mountains are now in most active process of growth, and in which, therefore, diastrophism is giving rise to those movements by which tectonic shocks are generated. It is in these belts, too, that most of the active volcanoes of the world lie, and, accordingly, it is here that the volcanic earthquakes must develop in greatest numbers. What causes the mountain growth and the location of volcanoes in these belts is a far more difficult question, and one to which definite answer cannot be given. It is noteworthy, however, that, in earlier ages, growing mountains and volcanic activity were distributed along different belts; for instance, when mountains rose and chains of volcanoes existed in eastern United States, in England, central France, and northwestern Germany. Then the belts of greatest earthquake intensity were doubtless far different from now.

That some regions are relatively immune from vigorous earthquakes is due to the fact that diastrophism and vulcanism are either absent or only moderately active. Minor shocks may rise from local causes, like those mentioned in discussing earthquake cause (p. 409); and if diastrophism is still in progress locally, as is apparently the case, even vigorous shocks may occur in regions outside the great earthquake belts. The earthquake belts lie in regions where, for some reason as yet unknown, earth movements are concentrated intensively; but some movement, less intense and less widespread, is occurring in other parts of the crust, and there occasional slipping gives rise to earthquakes, either great or small.

Earthquake Periodicity

The Desirability of Predicting Earthquakes. — It is a matter of high importance to determine whether there is any recognizable periodicity of earthquake occurrence, upon the basis of which it may be possible to make predictions. Up to the present time it is not possible to demonstrate such periodicity; but there are signs of a beginning which holds out promise of important future results, now that a large body of students are working upon seismological problems in all parts of the world.

Possible Relation to Atmospheric Pressure and Terrestrial Tides. — It has been suggested that there is a relation between variations in atmospheric pressure and earth shaking; and it seems reasonable to believe that, if a strain has been applied almost to the slipping point, change in the weight of air pressed down on that portion of the crust may give the necessary last cause for the movement. Variations in attraction upon the earth occur as the moon and sun change in relative position, as is well known from the phenomena of oceanic tides. Such variations may give the necessary last cause for slipping along a fault plane on which strain is already concentrated. It cannot be said that either of these causes is at present demonstrated; it will require a careful tabulation of a large mass of data to give such demonstration.

Relation to Shifting of the Poles. — Within recent years it has been proved that the pole is steadily changing position along a somewhat irregular path. As it changes there is necessarily a constant tendency for the earth form to change in adjustment to the new axis of rotation; and at certain points in the curve of the polar path there is such a change that there may well be sudden applications of pressure on parts of the crust. Milne has announced his belief that there is a well-defined periodicity of earthquake intensity related to this polar movement. A tabulation of the earthquake shocks of Japan indicate that periods of great seismic activity recur once in about 13 years; and for the city of Kioto, once in about half that time, or 6¼ years.

Theory of Alternation. — The eminent Japanese seismologist, Omori, has worked out a law, first applied to Japanese and Formosan earthquakes. This is that the stress applied along one of the great earthquake belts, on finding relief by an earthquake movement, will not for a time affect that neighbourhood; but when next the stress finds relief, it will be at a distant point along the belt. Upon the basis of this law he made the prediction shortly after the California earthquake of April 18, 1906, that the next great earthquake in that belt would occur in South America south of the equator. Immediately after this prediction came the great Chilean earthquake of August 17, 1906.

Relation to Vulcanism. — There are indications that there is sympathetic relationship between diastrophism and vulcanism, and that the mobile zone of flowage is affected by large, general causes, which react upon the rigid zone of fracture. The laws of behaviour of this mobile zone are not yet clear, but a beginning has been made, and in the study of seismology seems to lie one of the chief hopes for their discovery and demonstration. When these laws are understood, it may be possible to predict the times and places of occurrence of earthquakes and thus lead to great saving of life. Already the great zones of seismic intensity are marked out; and the location of many of the earthquake "rifts," or fault planes, is known. If the time when movements are likely to take place is known, and if the premonitory signs are understood and recorded, there need be no such terrible disaster as the world is made familiar with every now and then.

Elastic Rebound Theory. — Careful surveys of the region near San Francisco before and after the 1906 earthquake prove that for perhaps a century a slow northward movement had been taking place under the Pacific Ocean and in a strip along the west coast. This set up a shearing strain which finally became so great that faulting was renewed along an old line of fracture. The two sides then sprang back into positions of equilibrium, the rebound being distinguishable only within about 6 miles of the fault. Upon this is based Reid's elastic rebound theory of earthquakes. It may be stated as follows:

"1. The fracture of the rock, which causes a tectonic earthquake, is the result of elastic strains, greater than the strength of the rock can withstand, produced by the relative displacements of neighboring portions of the earth's crust. 2. These relative displacements are not produced suddenly at the time of the fracture, but attain their maximum amounts gradually during a more or less long period of time. 3. The only mass movements that occur at the time of the earthquake are the sudden elastic rebounds of the sides of the fracture towards positions of no-elastic strain; and these movements extend to distances of only a few miles from the fracture. 4. The earthquake vibrations originate in the surface of fracture; the surface from which they start has at first a very small area, which may quickly become very large, but at a rate not greater than the velocity of compressional elastic waves in the rock. 5. The energy liberated at the time of an earthquake was, immediately before the rupture, in the form of energy of elastic strain of the rock.

"These statements, which may be called the *elastic rebound theory* of tectonic earthquakes, do not broach the original cause of earthquakes, which lies in the source of the slow movements accumulating the elastic energy, but merely give the *modus operandi* of the accumulation and liberation of this energy." This theory offers promise of earthquake prediction.

Specific Instances

The Lisbon Earthquake. — One of the most terrible of recorded earthquakes occurred on November 1, 1755, at Lisbon, Portugal. A noise like thunder was first heard, then came a violent shock which threw down a large part of the city. The sea drew away from the land, then rolled in, rising 50 feet or more above the normal level. In less than six minutes 60,000 people perished. A large number of people gathered on a pier, or quay, to escape the danger from falling buildings; but a fissure opened beneath it, and it is said that it sank with all the people, and a number of vessels were drawn into the whirlpool and sank out of sight. The depth of water where the quay stood is said to have been 600 feet. The great water wave swept over the neighbouring coast; huge avalanches descended from the mountains; and the shock was felt as far away as Sweden, North Africa, and the West Indies. Previous earthquakes occurred in Lisbon in 1309 and 1531.

Southern Italy. — Earthquakes occur throughout Italy, some tectonic in character, others volcanic. Of the latter may be mentioned the earthquake which destroyed the town of Casamicciola on the volcanic island of Ischia in 1883. Although completely destroying the town, and much life, no damage was done in the city of Naples only 22 miles distant — showing clearly how limited is the area of destruction of volcanic shocks. Earthquakes are common before and during eruptions of Vesuvius and Etna.

Far more widespread and destructive are the Calabrian earthquakes south of Naples, where great tectonic shocks have occurred on numerous occasions. The earthquake of 1688 destroyed 20,000 lives; that of 1693, 43,000; that of 1783, 32,000, and there have been a series of shocks in the region down to that of 1905 in which 800 lives were lost, and the Messina earthquake of 1908 in which 100,000 lives are said to have been lost. In each of these great earthquakes the distribution of destructiveness has been along lines or narrow belts, one of which is the Strait of Messina, located on a fault line. It is not surprising, therefore, that Messina has been visited by a series of violent earthquakes, the last of which so completely devastated the city. It is a region in which crustal movements are actively in progress, and between two volcanic areas. There is indication that there is relationship between volcanic activity and diastrophic movements in this locality.

The Calabrian earthquake of 1783, which received careful study, presented some interesting phenomena. The ground cracked open and closed, the surface heaved in great undulations, and people were nauseated by the motion. Large trees swayed so that their tops touched the ground, monuments were twisted by vorticose motion, thousands of fissures and circular pits were formed on the surface, and water was forced out of the ground.

Other parts of Europe have earthquakes frequently, including Spain, England, Germany, and the Austrian Alps (Fig. 278). There are also frequent severe earthquakes in Asia Minor.

Indian Earthquakes. — Throughout the eastern Mediterranean and western Asia earthquakes are abundant and often of great violence; and it is well known that the Asiatic region was visited by destructive earthquakes in the days recorded in the Bible. The earthquake belt also extends through northern India. There was a great and destructive earthquake in the Indus valley in 1819, the shocks recurring through a period of 4 days. A great tract of land sank and another portion rose. In a few hours a tract of 2000 square miles was transformed to an inland sea, and an area 50 miles long, and in some parts 16 miles wide, was raised, to a maximum of 10 feet. A fort standing on the submerged area sank partly beneath the water.

A great earthquake, known as the Assam earthquake, occurred in India in June, 1897. There was a violent initial shock, and in 15 seconds practically all the destruction was accomplished, while the heavy shock had all passed in two minutes and a half. An area of 150,000 square miles was laid in ruins. The ground was fissured, and movements occurred along fault lines, in one place with a throw of 35 feet. One fault line extended parallel to a winding stream course. Where it crossed the stream it formed small ponds in some places where the upthrown side of the fault caused a dam; elsewhere where the stream fell from the upthrow to the downthrow side a waterfall resulted (Figs. 279, 280). The ground was heaved and moved, and railway tracks were twisted in a remarkable manner.

Another earthquake, known as the Kangra earthquake, devastated a great extent of country in northern India, on April 4, 1905, destroying 20,000 lives. It spread from two well-defined centres, and was felt over an area of 1,625,000 square miles. In this case there was no visible faulting at the surface, though there was a slight upward bulging of the surface in one of the centres.

Japanese Earthquakes. — Between India and Japan earthquakes are frequent and often very destructive in the East Indies and in the Philippine Islands. Japan is a centre of great seismic activity, and, owing to the destructive effects (Fig. 281), the study of seismology has received great attention there. On the average there has been one destructive shock in every two and a half years since the beginning of the seventeenth century, and there is record of 223 destructive shocks in the

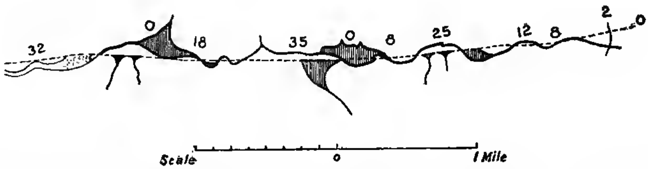


FIG. 279. — Ponds along fault scarp in India. Figures show amounts of uplift in feet. (Oldham.)

last 1500 years. In addition, there are vast numbers of lighter earthquakes, many detected only by the seismograph. Since 1885 there has been an average of 1400 shocks a year, or at the rate of about 4 a day.

Among these earthquakes that of October 28, 1891, known as the Mino-Owari earthquake, is notable as being one of the most destructive, and the first large earthquake to receive careful study by a trained seismologist. It shook an area of 243,000 square miles, or more than three-fifths of the entire area of Japan, but the area of great destruction was far smaller and was confined to a plain in a basin among the mountains in which lie the provinces of Mino and Owari, a densely settled plain with nearly a thousand people per square mile and a multitude of villages. The earthquake came without warning, and in a single minute 20,000 buildings were thrown down, 7000 people were killed, and 17,000 injured. Fire followed, as is often the case after earthquakes, and added to the destruction of life and property.

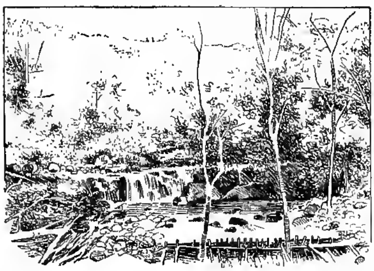


FIG. 280. — Waterfall over fault scarp, formed during Assam earthquake of 1897. (Oldham.)

As in the case of many earthquakes, there was a succession of aftershocks, 102 on October 28, 318 on October 29, and a decreasing number for several months afterwards. Over 2500 shocks were recorded at the city of Gifu within the period of five months succeeding the great earthquake.

The ground was cracked and fissured, mud volcanoes and sand craters were developed, and subterranean drainage was interfered with. Even the light bamboo houses were thrown down, railroad bridges were broken and caused to collapse, and a railway track was bent into a sinuous, serpentine course. A long fault line, extending in a northwest-southeast course, was traced a distance of 40 miles by the disturbance of the surface. On one side of the fault the surface sank from 2 to 20 feet (Fig. 282), the fault line being marked sometimes by a cliff, sometimes by a cracked and fissured dome. There was also lateral shifting along the fault line, movement occurring in a northerly direction on the average from 3 to 6 feet, and in one place 12 feet.

FIG. 281. — Building destroyed by one of the Japanese earthquakes.

Alaskan Earthquakes. — The earthquake belt of Japan swings along the Aleutian chain to the Alaskan coast region, and throughout the Aleutian Islands and the coast of Alaska earthquakes are abundant, and often of great violence. Owing to the sparsely settled character of this region, little attention has been paid to these earthquakes. The single exception is the series of shocks that affected the St. Elias region in September, 1899, and that, originating in the Yakutat Bay region, are known as the Yakutat Bay earthquakes. Although no destruction of life occurred, and almost no damage was done to property, these are to be reckoned among the most notable of modern earthquakes. They were of such strength that they attracted attention in Europe from the seismographic records alone, and the place and time of their occurrence were determined even before anything was known about the remarkable phenomena associated with them.

During these earthquakes, which occurred in a period of 27 days, from September 3 to 29, there were four or five that were world shaking, and hundreds of minor shocks. There were especially violent shocks on September 3, 10, and 23, and strong earthquakes also on the 15th, 17th, 26th, and 29th. Two world-shaking earthquakes occurred on the 10th. The violent shocks were recorded on seismo-

FIG. 282. — Fault made during the Japanese earthquake of 1891. (Milne and Burton.)

graphs all over the earth, and an area of at least 400,000 or 500,000 square miles was sensibly shaken, and perhaps 3 times that area.

As already stated (p. 394), the neighbouring shorelines were notably deformed (Fig. 283), in one place being uplifted 47 feet, in other places being depressed. The crust was broken and moved along a series of fault planes and the mountain blocks tilted, a part of the movement of the growing St. Elias Range. Besides major fault lines there was a series of smaller fissures and faults, some with a throw of over 3 feet. Vast quantities of snow, ice, and rock were avalanched from the mountains, and, as a result of this abrupt accession of supply to the reservoirs of the glaciers, a wave of advance was started which during succeeding years swept down the glaciers and caused notable change and advance in the glacier ends.

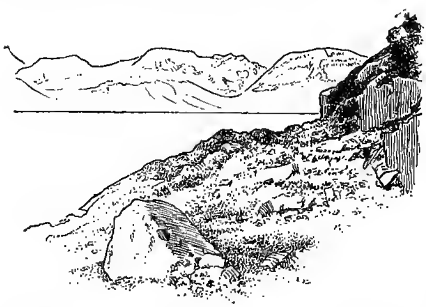


FIG. 283. — Elevated sea cliff and rock bench which was raised over 17 feet in Yakutat Bay earthquake of 1899.

At least one great water wave swept through Yakutat Bay and tore up the forest to an elevation of 50 feet in some places (Fig. 284). Only a small group of prospectors were in the bay at the time, and their escape from death was marvellous. From them and from the inhabitants of the native village at the mouth of the bay we have the only direct knowledge of these earthquakes in this central area; but information concerning the shaking in other sections has been obtained from a number of people. Both in Yakutat Bay and at Muir Glacier the vigorous shaking dislodged huge masses from the tidal glaciers.

South American Earthquakes. — The western coast of South America is another noted seismic area, and has been the seat of repeated

Fig. 284. — Forest destroyed by earthquake water wave, or tsunami; and scars of avalanches on mountain side, Yakutat Bay, Alaska.

shocks, some of great violence and destructiveness. In Chile, for instance, a great earthquake occurred on May 24, 1751, and the coast was devastated by an earthquake water wave that rolled in upon it. A violent earthquake occurred in Peru on October 28, 1746, during which Lima was destroyed. Nineteen ships were sunk in the harbour of Callao, and most of the 4000 inhabitants of the city were destroyed. In 1687, 59 years earlier, Callao was also overwhelmed by an earthquake and accompanying water wave. Chile was visited by other destructive shocks in 1822, 1835, and 1837. During the earthquake of February 20, 1835, there was also a destructive water wave; and the island of Juan Fernandez 865 miles from Chile was also violently shaken, while a submarine volcano broke forth about a mile from the shore. An earthquake in Peru and Ecuador in 1868 affected a strip of country 2000 miles long. Since then there have been other earthquakes on the western coast of South America, the last being the Valparaiso earthquake of 1906.

The occurrence of the water waves proves that at least a part of the movement in the earthquake occurred beneath the sea. It is probable that there is subsidence of the sea bottom along this steeply rising coast; and uplifted shorelines prove that there has also been recent rising of the land. It is a noteworthy fact that many of the belts of greatest seismic activity are on or in close association with steep slopes, along which subsidence is apparently in progress on one side and uplift on the other.

West Indian Region. — Central America, northern South America, and the West Indies form another region of frequent earthquakes, some on the land, some on the sea floor. There have been numerous severe earthquakes in this region, some of them evidently volcanic, as in Guatemala, where the site of the capital, near the base of a volcano, had to be changed because of the frequency of destructive earthquakes. Others are of tectonic origin. Such was probably the case in the earthquake which destroyed Caracas in 1812, and killed 10,000 people in about half a minute.

Earthquakes have occurred in islands and the surrounding waters. Jamaica has suffered especially in this respect. Up to 1692 the capital of the island, Port Royal, stood at the entrance to Jamaica harbour, partly on a low rocky point, partly on a sand bar connecting the rock with the main island. In 1692 a violent earthquake visited the island, causing the land to rise and fall "like a rolling sea," landslides fell from the neighbouring mountains, houses were thrown down, and fissures opened and closed, in some of which people were caught and entombed. The part of Port Royal that stood on the sand bar slid into the water, something like 1000 acres of land being thus engulfed, and for years afterward it is said that the chimney tops of the houses could be seen in the waters of the harbour.

The new capital, Kingston, was built at the head of the bay, and it was visited by an earthquake of great vigour on January 14, 1907. First there came slight preliminary tremors, then in about ten seconds a shock so violent that persons were thrown to the ground. In thirty-five seconds all damage by the shaking had been accomplished, but then fires broke out and destroyed a large part of the city. On and near the site of the former Port Royal there was extensive subsidence, palm trees being lowered beneath the water. The depth of the harbour was also increased, in one place being 27 feet deeper than before the earthquake.

Earthquakes in Eastern United States. — The greater part of the United States is apparently free from the danger of violent earthquakes. Earth tremors and minor shocks are common, and in some places are especially frequent, as in the neighbourhood of East Haddam, Connecticut (Fig. 285). There have also been some shocks of considerable violence. The earliest of these of which we have record occurred on February 5, 1663, and, although central in the St. Lawrence valley, was felt also in New England. It seems to have been a shock of catastrophic violence, judging from the accounts of it kept by the Jesuit priests.

Three shocks of considerable violence occurred in New England in 1685, 1727, and 1755, respectively. The second affected the region near Newburyport, Mass., and is reported as having consisted of a series of successive shocks, through a period of four years, some hundreds in all, and some of them quite violent. Contemporary accounts refer to accompanying strange noises described by Shaler as follows: "There came from the earth a wonderful thundering, or bellowing noise, loud enough to startle people from sleep, even when they had long been used to it. Many believed that it was the Evil One himself, raving in his empire beneath the earth, and threatening to burst it asunder in his rage." Sounds accompanying earthquakes, and coming from underground sources, are reported as occurring in association with many earthquakes.

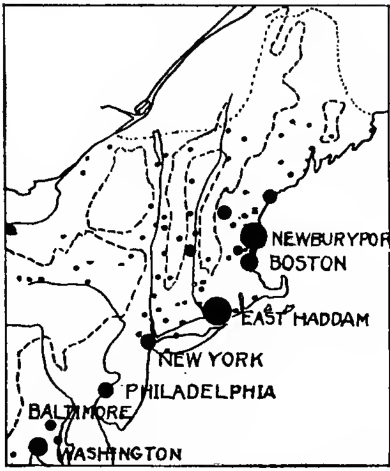


FIG. 285. — Seismicity of New England. Frequency of earthquakes indicated by sizes of black dots. (de Montessus de Ballore.)

The shock of 1755 was most violent near Boston, and is reported to have been strong enough to throw people from their feet, but little destruction was accomplished by it.

In 1811–1812 there occurred a series of violent shocks in the lower Mississippi valley, commonly referred to as the New Madrid earthquake. The region (Fig. 286) now embracing parts of northern Arkansas, southern Missouri, and western Kentucky and Tennessee, was sparsely settled, and, therefore, little destruction was accom-

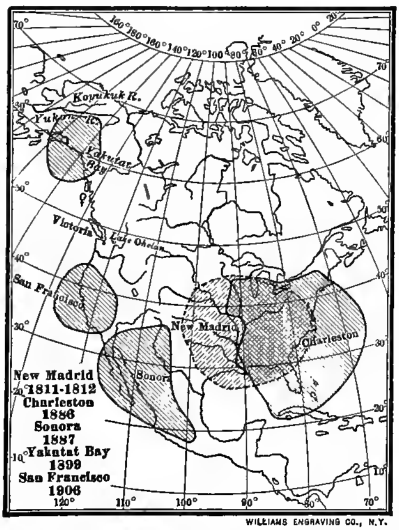


FIG. 286. — Map showing as much as is known of the area affected by the New Madrid earthquakes in 1811–1812, and comparison with four other great seismic disturbances in North America.

plished, though some of these shocks were evidently of the world-shaking order. The first shock occurred on the night of December 16, 1811, and from that time till March 16, 1812, there were 1874 recorded shocks, of which eight were of the first order of violence, the most violent being February 7. These earthquakes were so violent that they were felt throughout eastern United States. The ground opened in long fissures, and water spouted out of them to heights as great as 40 feet. A large area of country was depressed, and is still called the "sunk country," while lakes still exist which were formed at the time (p. 316), with trees still standing in them.

Fig. 287. — Destruction of buildings during the Charleston earthquake in 1886. (Hillers, U. S. Geol. Survey.)

Lesser shocks have occurred in this region since, and it is evident that this is a region of seismic activity in the midst of a country in the main exempt from the danger of violent earthquakes.

The last notable earthquake to affect eastern United States was central near Charleston, S.C., August 31, 1886, and is commonly known as the Charleston earthquake. Strange noises were heard and slight tremors were felt before the earthquake, notably on August 27 and 28. Just before ten o'clock at night on the 31st a rumbling sound was heard, increasing to a great roar, and the shaking became violent. There was a second violent shock a few minutes afterwards, and a number of after shocks of lesser violence.

The earthquake spread at the rate of about 150 miles per minute, from two epicentra a few miles westward from Charleston, and the shaking was felt over much of eastern United States, the total shaken area being between two and three million square miles. The usual phenomena of fissures and craterlets were developed in the area of vigorous shaking, and railway tracks were bent and buckled, giving evidence of lateral shifting.

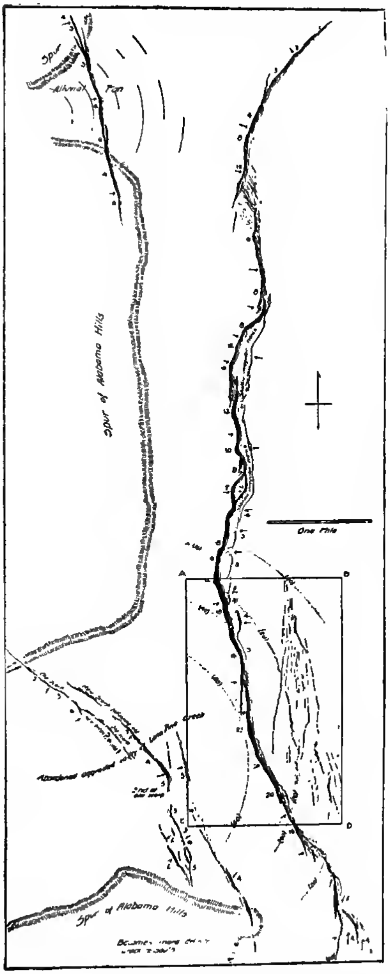


FIG. 289. — Map of fault scarps at Owens Valley, California. Figures give height of scarps. (W. H. Hobbs, after W. D. Johnson.)

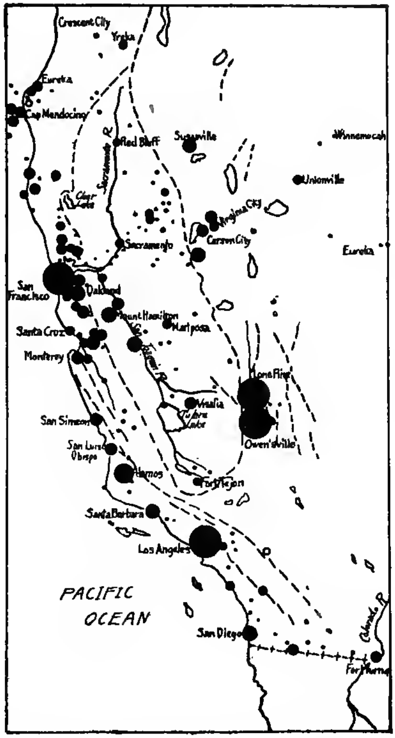
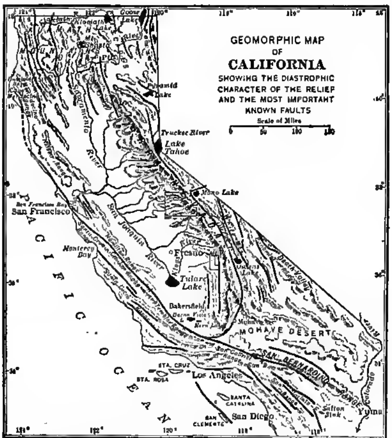


FIG. 288. — Diagram showing by size of the black dots the frequency of earthquakes in California. (de Montessus de Ballore.)

Although a violent earthquake, and one that affected a wide area and therefore received careful study, the Charleston shock probably does not rank among the most violent. Some damage was done to most of the large buildings in the city, but few were destroyed (Fig. 287), and only 27 lives were lost. One of the chief kinds of damage was the destruction of chimneys, there being about 14,000 of these thrown down.

Earthquakes in Western United States. — The country from the Rocky Mountains westward to the Pacific is a seismic region, though throughout most of it no really destructive earthquake has occurred during the period of settlement. There are, however, fault scarps which indicate recent movement, and earthquakes in almost any part of the region need not be unexpected.

One of the greatest earthquakes of the West occurred March 26, 1872, in Owens Valley, California. Fault scarps were developed here (Fig. 289), and the disturbance of the surface during this earthquake is still plainly to be seen. It was a sparsely settled region and little destruction was therefore accomplished, though it doubtless ranks among the great earthquakes of recent times. The Sonora earthquake of 1887 was also very severe, being felt over an area of 500,000 square miles (Fig. 286) in Mexico and southwestern United States.



Map of California. The heavy lines indicate the principal faults.

FIG. 290. — Fault lines in California. (Lawson.)

The Coast Ranges of the Pacific coast have been the seat of a number of vigorous earthquake shocks since the region was settled, and there are well recognizable rift valleys and fault scarps along which movement has recently taken place. In this region the section of central western California, in and near San Francisco, is a centre of special frequency of earthquake shaking. Scores of earthquakes have occurred in that centre, and several of them have been of destructive violence, the last one being that of April 18, 1906 (Figs. 288, 290).

During this shock there was horizontal shifting of a large mass of country on the southwest side of a fault plane, the movement being generally in a northeastward direction, and varying from 3 to 20 feet. At one point there was movement in the opposite direction, and locally there was uplift on one side, but nowhere more than 4 feet. The fault line, or rift, or "earthquake crack," or fault trace, was followed across country by the furrowing of the surface, the dislocation of the roads, breaking of water pipes, separating of fences, and even the splitting of trees beneath which it passed (Figs. 270, 292).

This great rift, traced for about 400 miles, has been the seat of earlier movements, at least as far back as the Glacial Period, and its course is marked by a succession of linear valleys, small lakes and pools, fault scarps, and narrow bays. Doubtless there have been many earlier earthquakes as a result of movements along this line; and it is probably a safe prophecy to state that there will be others in the future.

The rift runs just west of San Francisco, and, therefore, the movement along it caused severe shaking in the city, and much destruction

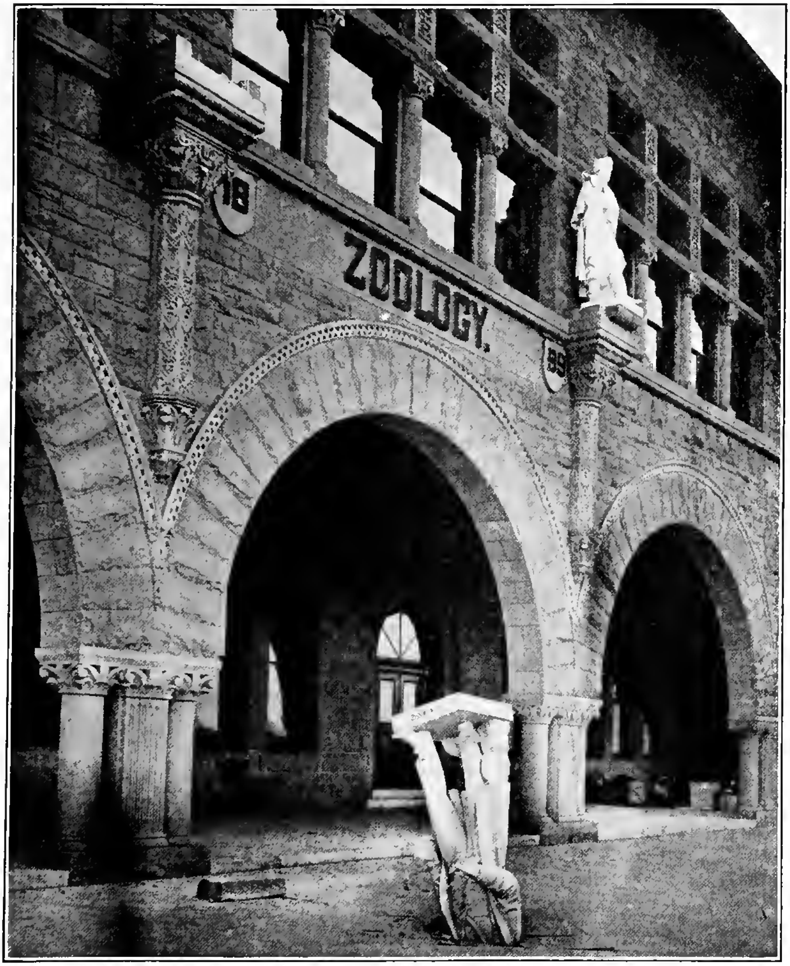


FIG. 291. — The Agassiz statue at Leland Stanford Junior University after the California earthquake of 1906. (Davey.)

there. The greatest damage was, however, accomplished by the fire that followed the earthquake, for, as is so commonly the case, fire broke out at several points in the damaged city, and spread with great rapidity and destructiveness, increased by the fact that the city water supply was cut off by the breaking of the mains by the earth movement. The city was laid mainly in ruin; it would have been well if the new city had been built up with the possibility of a future

Fig. 292. — Horizontal shifting of a road in California. Before the 1906 earthquake this road was straight. (Sinclair.)

recurrence of a similar disaster in mind. The destruction of San Francisco by earthquake and resulting fire stands out as one of the great human disasters, and the greatest to which the United States has been subjected as a result of the terrible natural phenomenon of earthquake shaking (Figs. 275, 293). Fortunately there was no earthquake water wave in connection with this seismic disturbance.

Earthquake Water Waves

Earthquakes below Sea Level. — It is a well-known fact that earthquakes originate on the ocean floor as well as on the land. The occurrence of such shocks is sometimes observed on shipboard; telegraph cables are sometimes snapped apart by submarine movements; and the seismographic records of the present day have located many such shocks. Another proof of such shocks is the development of *earthquake water waves*, or *tsunami*, sometimes spoken of as "tidal waves." Such submarine earthquakes are most common in the two great earthquake belts, and especially in places where there are abrupt changes

Fig. 293. — Train overturned during the California earthquake of 1906. (Gilbert, U. S. Geol. Survey.)

in the slope of the ocean floor, along which fault movements are evidently taking place. In some sections of the sea bottom there are very abrupt slopes, and even great precipices, as in the neighbourhood of Zante in the Mediterranean, where there are submarine cliffs from 3000 to 5000 feet high. The cable between Zante and Crete has several times been broken by movements along submarine fault planes; and in some parts of the sea bottom the floor is so uneven that it is not feasible to lay cables on it.

Nature of the Water Wave. — When such a movement takes place beneath the sea, the entire body of water above is lifted or lowered with the moving crust. Thus a broad, low swell is formed, affecting the ocean from top to bottom. It is so low that its passage would not be noticed, unless concentrated by movement into shallow water. If originating in the open sea, since it spreads outward in all directions from the centre, it may be dissipated before travelling a great distance; but if it starts near the coast, it may rise in height on passing into the shoaling water near shore, and rush upon the land as a great and destructive surge.

Large Areas Affected. — Although such destructive inundations are possible only on coasts near the centre of disturbance, the great wave may sweep completely across the oceans, and cause recognizable fluctuations in the tide gauges on the opposite shores. The wave generated during the explosion of the volcano Krakatoa in 1883, for example, was measured on all the tide gauges of the Pacific and Indian oceans; and the water wave generated during the Lisbon earthquake of 1755 is said to have swept all the coasts of the civilized world. Their great extent, and their destructiveness on near-by coasts, are due to the fact that they differ from ordinary waves in

FIG. 294. — The *Wateree* washed ashore during the Chilean earthquake of 1868. The surf line is an eighth of a mile beyond the farther ship.

being a motion of the whole body of the ocean water from top to bottom, not of the upper layers alone. At sea they will pass unnoticed because so low, but on the shallowing coasts the great body of water involved causes a piling up of the water as the more slowly moving tide does at regular intervals.

Damage to Life and Property. — Instances of such waves have been mentioned in the preceding pages; for instance, the earthquake water wave that devastated Lisbon, the similar waves on the coast of South America, and the water wave that swept through Yakutat Bay. Such waves have also swept portions of the coast of Japan, and other portions of the Asiatic coast. During the inundation of a tsunami on the coast of Japan in 1896, the earthquake water wave 10 to 50 feet high devastated 175 miles of coast, wrecked 9300 houses, stranded 300 large crafts, and crushed or carried away 10,000 fishing boats, and killed 27,000 people. A water wave during the South

American earthquake of 1868 carried a United States warship inland half a mile, leaving it stranded (Fig. 294). By such waves trees and buildings are torn loose and floated about, and complete devastation follows in the wake of the rushing waters, which may rise 50 to 100 feet above normal tide level.

References to Literature

J. G. Aguilera. Sonoran Earthquake, De los Fenómenos Seismicos del 3 de Mayo de 1887, Anales del Ministerio de Fomento, Vol. 10, Mexico, 1888, pp. 5–56.

M. Baratta. La Catastrope Sismico Calabro Messine, Rome, 1910.

W. M. Davis. Nomenclature of Surface Forms on Faulted Structures, Bull. Geol. Soc. Amer., Vol. 24, 1913, pp. 187–216.

C. Davison. A Study of Recent Earthquakes, London, 1905, 355 pp.

C. E. Dutton. The Charleston Earthquake of August 31, 1886, 9th Ann. Rept., U. S. Geol. Survey, 1889, pp. 203–528; Earthquakes, in the Light of the New Seismology, New York, 1904, 314 pp.

M. L. Fuller. Our Greatest Earthquakes, Pop. Sci. Monthly, Vol. 69, 1906, pp. 76–86; Notes on the Jamaica Earthquake, Journ. Geol., Vol. 15, 1907, pp. 696–721; The New Madrid Earthquake, Bull. 494, U. S. Geol. Survey, 1912, 119 pp.

J. Geikie. Structural and Field Geology, New York, 1905, 435 pp.

G. K. Gilbert. Modification of the Great Lakes by Earth Movement, Nat. Geog. Mag., Vol. 8, 1897, pp. 233–247; Recent Earth Movement in the Great Lakes Region, 18th Ann. Rept., U. S. Geol. Survey, Part 2, 1897, pp. 595–647; A Theory of Earthquakes of the Great Basin, Amer. Journ. Sci., Vol. 27, 1884, pp. 49–53; Earthquake Forecasts, Science, Vol. 29, 1909, pp. 121–138.

G. K. Gilbert and Others. The San Francisco Earthquake and Fire of April 18, 1906, Bull. 324, U. S. Geol. Survey, 1907, 161 pp.

J. W. Gregory. The Great Rift Valley, London, 1896, 422 pp.

J. F. Hayford. The Earth Movements in the California Earthquake of 1906, U. S. Coast and Geodetic Survey, Rept. for 1907, Appendix 3, 1908, pp. 67–104.

W. H. Hobbs. Earthquakes, New York, 1907, 336 pp.; Some Principles of Seismic Geology, Beiträge zur Geophysik, Vol. 8, 1907, pp. 219–362; A Study of the Damage to Bridges during Earthquakes, Journ. Geol., Vol. 16, 1908, pp. 636–653; The Evolution and the Outlook of Seismic Geology, Proc. Amer. Phil. Soc., Vol. 48, 1909, 44 pp.; The Earthquake of 1872 in the Owens Valley, California, Beiträge zur Geophysik, Vol. 10, 1910, pp. 352–385.

R. Hoernes. Erdbebenkunde, Leipzig, 1893, 452 pp.

E. Huntington and J. W. Goldthwait. The Hurricane Fault in Southwestern Utah, Journ. Geol., Vol. 11, 1903, pp. 46–63; *ibid.*, Bull. Mus. Comp. Zoöl., Vol. 42, 1904, pp. 199–259.

C. G. Knott. The Physics of Earthquake Phenomena, Oxford, 1908, 283 pp.

K. Kobayashi. Report on Earthquake Observations in Japan, Tokio, 1892, 43 pp.

B. Kotô. On the Cause of the Great Earthquake in Central Japan, 1891, Journ. College of Science, Imperial University, Japan, Vol. 5, Part 4, 1893, pp. 295–353.

A. C. Lawson. Post-glacial Faults near Banning, Ontario, Bull. Seism. Soc. Amer., Vol. 1, 1911, pp. 159–166; Recent Fault Scarps at Genoa, Nevada, *ibid.*, Vol. 2, 1912, pp. 193–200.

A. C. Lawson and Others. The California Earthquake of April 18, 1906, 2 vols. and atlas, Publication 87, Carnegie Institution, 1908, 1910, 451, 192 pp.

C. K. Leith. Structural Geology, New York, 1913, 161 pp.

Sir Charles Lyell. Lisbon Earthquake, Principles of Geology, 11th edition, Vol. 2, 1874, pp. 147–154; Temple of Jupiter Serapis at Pozzuoli, *ibid.*, Vol. 2, pp. 164–178.

Lawrence Martin. Alaskan Earthquakes of 1899, Bull. Geol. Soc. Amer., Vol. 21, 1910, pp. 339–406; Possible Oblique Minor Faulting in Alaska, Economic Geology, Vol. 2, 1907, pp. 576–579.

C. S. Middlemiss. The Kangra Earthquake of April 4, 1905, Memoir 38, Geol. Survey of India, Calcutta, 1910, 409 pp.

J. Milne. Earthquakes, New York, 1886, 363 pp.; Seismology, London, 1898, 320 pp.; Recent Advances in Seismology, Proc. Royal Soc. A, Vol. 77, 1906, pp. 370–373; Movements of the Earth's Crust, Geog. Journ., Vol. 7, 1896, pp. 229–250; Recent Earthquakes, Nature, Vol. 77, 1908, pp. 592–597.

J. Milne and W. K. Burton. The Great Earthquake in Japan, 1891, 2d edition, Yokohama, 30 plates, 70 pp.

F. de Montessus de Ballore. Les Tremblementes de Terre, Paris, 1906, 475 pp.; La Science Seismologique, Paris, 1907, 579 pp.

R. D. Oldham. Report on the Great Earthquake of 12th June, 1897, Memoir 19, Geol. Survey of India, Calcutta, 1899, 379 pp.; The Geological Interpretation of the Earth Movements Associated with the Californian Earthquake of April 18th, 1906, Quart. Journ. Geol. Soc., Vol. 65, 1909, pp. 1–20.

F. Omori. Bulletins of the Imperial Earthquake Investigation Committee, Tokio, 1907 to date; also Publications of the Earthquake Investigation Committee in Foreign Languages.

H. F. Reid. The Mechanics of the (California) Earthquake, Carnegie Institution, Publication 87, Vol. 2, 1910, 192 pp.; The Elastic Rebound Theory of Earthquakes, Bull. 6, Dept. Geol. Univ. Cal., 1911, pp. 413–444.

E. R. Scidmore. The Recent Earthquake Wave on the Coast of Japan, Nat. Geog. Mag., Vol. 7, 1896, pp. 285–289.

N. S. Shaler. The Stability of the Earth, Aspects of the Earth, New York, 1904, pp. 1–45; First Book in Geology, Boston, 1885, pp. 130–140.

A. Sieberg. Handbuch der Erdbebenkunde, Brunswick, 1904, 362 pp.

R. S. Tarr. Pacific Coast Earthquakes, The Independent, Vol. 60, 1906, pp. 954–962; The World's Earthquake Belts and Causes of Seismic Shocks, Leslie's Weekly, Vol. 103, 1906, pp. 422–423.

R. S. Tarr and Lawrence Martin. The Earthquakes at Yakutat Bay, Alaska, in September, 1899, Prof. Paper 69, U. S. Geol. Survey, Washington, 1912, 135 pp.

C. R. Van Hise. Earth Movements, Trans. Wis. Acad., Vol. 11, 1898, pp. 465–516.

B. Willis. Mechanics of Appalachian Structure, 13th Ann. Rept., U. S. Geol. Survey, Part 2, 1892, pp. 211–281.

J. B. Woodworth. Postglacial Faults of Eastern New York, Bull. 107, N. Y. State Museum, 1907, pp. 5–28.

C. W. Wright. The World's Most Cruel Earthquake (Messina), Nat. Geog. Mag., Vol. 20, 1909, pp. 373–396.

PERIODICALS

Bulletin Seismological Society of America, Palo Alto, Cal.

Gerland's Beiträge zur Geophysik, Leipzig.

Transactions Seismological Society of Japan; Seismological Journal of Japan.

Bollettino della Società Sismologica Italiana, Rome.

Die Erdbebenwarte, Vienna.

TOPOGRAPHIC MAPS

For topographic maps showing the fault trace of the California earthquake of 1906 on U. S. Geol. Survey quadrangles and on special contour maps by F. E. Matthes, see atlas accompanying report on California earthquake of 1906, Publication 87, Carnegie Institution. For hachure maps of fault scarps in Owens Valley by W. D. Johnson, see Hobbs' Earthquakes, and his paper on Owens Valley earthquake. For maps showing relations of topography to various folded and faulted structures, see the folios of the U. S. Geol. Survey. For topographic maps of fault scarps and fault block mountains, see the end of Chapter XV.

CHAPTER XIII

VULCANISM

Nature of Vulcanism

Lava Blown into the Air. — In some parts of the earth molten rock or *lava* rises to the surface and spreads out over the surrounding country. It is always accompanied by steam (Fig. 295) and other gases, the expansion of which is commonly responsible for the

Fig. 295. — Katmai volcano, Alaska, in eruption in June, 1913. (M. Horner.)

expulsion of the liquid rock. In some cases the expansion of the associated gases blows the lava into bits which settle around the orifice as *volcanic ash*, pumice, and lava blocks of various sizes and shapes. These are usually very porous because of the expansion of the included gases.

Lava Flowing out of Openings. — In other cases the liquid rock flows out more quietly as a *lava flow*, from which great quantities of steam rise, and in the upper portion of which a porous condition is also caused by the expanding of the gases as the lava cools.

In recent geological periods lava rose to the surface through cracks, or fissures, and spread over the surrounding region in great floods; but at present this condition is practically unknown, though some of the modern eruptions of Iceland have come from fissures, or from numerous vents along fissures.

Lava Building up Cones. — The surface expressions of vulcanism to-day are mainly those of eruption from restricted vents, which we call *volcanoes.* These volcanoes are, however, often along lines, as if associated with fissures, from only portions of which is there emission of lava at present. Very often in a chain of volcanoes only one or two are now active, and in some cases activity is apparently at an end in all the volcanoes of a chain. In some cases, at least, it seems as if a fissure had opened, from many parts of which lava outflowed; then, with diminution of the expelling force, eruption was confined to a few points along the fissures; and, finally, one after the other of the vents became closed. A final stage in volcanicity is the escape of steam, sulphurous and other gases, and hot water.

Lava Underground. — Besides the form of vulcanism which is expressed in surface outflow, there are underground manifestations of importance, the nature of which will not be considered for the present.

The Volcanic Products

The two products of volcanic eruption are molten rock and associated gases, each appearing in different forms according to conditions.

The Lava Flow. — Where the lava rises in sufficiently liquid condition, it flows away from the vent, as molten iron would flow. At first, while hot, it cools to a dull red glow, then to a rock either black or other colour, passing from the liquid to the pasty and then to the solid state, when it may be crystalline or glassy. On issuing from the vent, the temperature may be 2000° F. or more; but by radiation and conduction it rapidly cools as it flows away from the vent and spreads out; but it may be months and even years before a lava flow becomes completely cold. The lava may be solid enough to walk upon, while glowing hot within. The lava crust is such a poor conductor that it requires a very long period for it to completely cool. For example, the lava from the eruption of Vesuvius in 1787 was still hot and steaming seven years later; steam still issued from the flow of 1858 when observed by Geikie in 1870; and it is said that 21 years after a lava flow issued from the volcano Jorullo in Mexico, in 1759, a cigar could still be lighted at its fissures, and it was still steaming 44 years after the eruption.

Gases from Lava Flows. — From the moment the lava reaches to the surface until after it has become completely solidified, steam and other gases rise from it; and at first so much steam may rise that the lava flow is almost completely covered by an overhanging cloud. While the lava is liquid, these gases may escape without any effect on the lava, though there may be minor eruptions from the surface as the highly heated gases rapidly escape, or where the lava flows over snow, or springs, or other bodies of water. When it becomes pasty, the escaping gases may form cavities which do not close, giving rise to porous, slaggy, or cinder-like texture. When solid, the gases cease to escape, excepting from the crevices and fissures, some of which open as the solidified lava cools and contracts.

Pahoehoe and Aa. — If a part of the liquid lava cools without further movement during the pasty or solidified state, it will assume a smooth, or fairly regularly rounded surface, called, in the Hawaiian Islands, *pahoehoe;* but usually there is subsequent flow, and the surface, therefore, becomes much rougher. Flow during the pasty state draws the partially solidified lava out in the form which is well described by the term *ropy structure*, the surface resembling the braided form of a coarse rope or coil of rope, due to the stretching of the nearly solid rock. A solid crust may form while there is still liquid lava below; and then, if motion continues, the crust may be fissured, broken, and splintered, giving rise to a field of clinker-like fragments. Such a rough lava surface is called *aa* in the Hawaiian Islands. During such a stage in lava flow motion, one can hear the blocks break and grind together.

Variations in Lavas. — There are many differences in the appearance of a recently formed lava flow, partly for the reasons stated, partly because the lavas vary in composition, in temperature, and in the slope over which they flow. Some lavas are quite viscous, even at the point of emission, as in the case of Vesuvius; and such lavas are normally rough and clinkery. Others are more liquid, like the Hawaiian lavas, and in these the smoother form is more common, while the lavas spread out in a thinner sheet. The degree of liquidity may be due either to difference in temperature or to difference in composition. The basic lavas, or *basalts*, of the Hawaiian Islands, for example, melt at a lower temperature than the more acid lavas. There is a difference in rate of flow also according to the slope, as in the case of any liquid body.

Rapidity of Flow. — A lava flow may escape from the crest of a volcano, but much more commonly it issues from one or more fissures on the slopes of the cone. It may well out with moderate volume, or it may spout out fountain-like, especially where it issues from the lower flanks of a volcano and is, therefore, under hydrostatic pressure from the column standing in the volcanic vent. For instance, in the eruption of Mauna Loa in 1852, a fountain of lava 1000 feet broad rose to a height of 200 to 700 feet. At the same time vast volumes of steam escape and condense in a heavy cloud over the white-hot lava. At first the lava flows down the slopes rapidly, spreading as it goes, naturally seeking the lowest points, and, therefore, entering any valleys that may lie in its course. It is reported that it may flow as fast as a mile a minute, though the rate is ordinarily less rapid, moving near the point of outflow from ten to fifteen miles an hour. A lava flow from Etna in September, 1911, moved as a stream 1500 to 1800 feet wide, 35 to 45 feet high at the front, advancing ¼ of a mile an hour. Still slower rates are the rule, the lava at Teneriffe in the Canary Islands in 1909 flowing only 50 or 60 feet an hour on a 10° slope.

Cooling of Lava Flows. — As a crust forms on the lava, its rate of flow diminishes, and finally the forward motion of the end may be almost imperceptible. The advancing end is apparently a broken mass of lava blocks, slowly pushing forward with an accompanying sound of rupturing and grinding of the solid mass urged forward by the underflow of the liquid lava. If it comes to the edge of a steep slope, or if for any other reason the front is ruptured, the liquid lava may rush forth with rapid flow from beneath the pile of broken fragments, overwhelming all in its path. This outrush of lava sometimes leaves caverns beneath a solidified roof, and in the Hawaiian volcanoes they are at times ornamented with lava stalactites and stalagmites.

Size of Flows. — Lava flows commonly extend only part way down the slopes of volcanoes, though now and then they flow out to the surrounding land. Some of the large lava flows of the Hawaiian Islands are 30 or 40 miles long, and two or three miles broad. Dana estimates that the flow of 1852 from Mauna Loa may have contained as much as 10,560,000,000 cubic feet of lava, assuming its average width to be 6000 feet and its average depth 20 feet. Daly states that Mauna Loa emitted 455 million cubic metres in 1855; that the lava from Skaptar Jökull in Iceland in 1783 amounted to 12,360,000,000 cubic metres; and that Etna sent out 980 million cubic metres in 1669, or 34,608,160,000 cubic feet.

Effects of Flows. — The lava flow overwhelms everything in its path, and leaves a train of destruction, blotting out not only plants and human structures, but even completely changing the topography. There are few more desolate scenes than that of a recently formed lava flow; and it is many years before a new soil can form on its surface and vegetation once more occupy it. This varies with the lava, some of the streams from Vesuvius being occupied in less than a century; others, as in Sicily, remain barren for centuries. Where the flow ends, however, trees may still stand, for the heated lava is buried beneath the solidified crust, and the vegetation is not injured unless the end of the flow overturns and overrides it. Even islands of trees and vineyards may stand in the midst of a lava flow that has surrounded them. Lavas have even flowed over snow fields and ice, without melting them. On the slopes of Etna, for example, there is a mass of ice, originally a snow bank, which was buried by a lava flow over a century ago. At other times the lava melts the snow, causing great floods; and, by the steam thus caused, eruption occurs within the flow itself. Small cones are thus sometimes formed on the surface of lava flows where the liquid rock flowed over and evaporated snow or water. In a few minutes a lava flow may blot out a valley, and bury it beneath hundreds of feet of rock. By entering the sea, the lava may notably extend the land area, as in 1868, when a half mile was added to a portion of the island of Hawaii, and in 1906 when a lava flow from the island of Savaii poured into the sea for several weeks, extending the coast (Fig. 296). The lava streams often form dams across valleys in which lakes gather; and they at times force streams to outflow

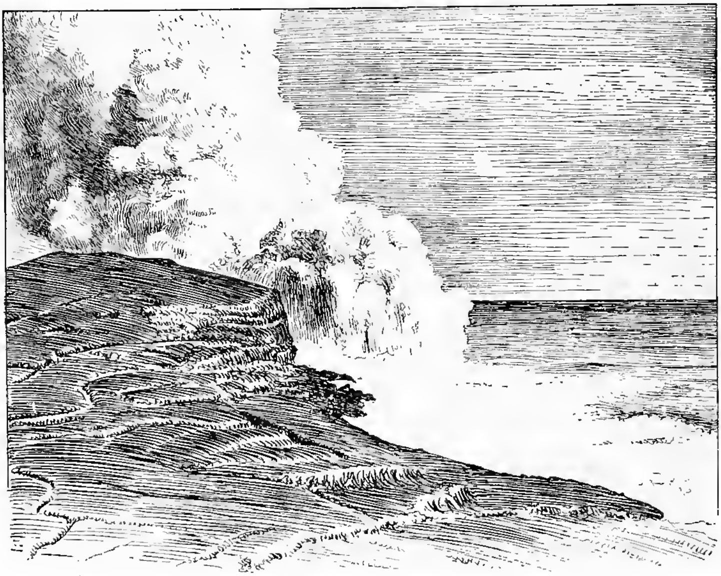


FIG. 296. — Lava flow entering the sea in Savaii. (After Sapper.)

across low portions of their valley wall, thus dividing their courses, or even inverting their flow by turning them so that they outflow across former divides.

Fragmental Products. — Even as lava is flowing, the explosive action of included water frequently throws fragments into the air and even builds small cones of such ejecta on the surface of the lava flow. Similarly, though on a far grander scale, lava fragments are hurled from the volcanic vents, and as they rise the expansion of the included water renders the lava porous, forming volcanic ash. Although the name ash is used, it is not to be implied that combustion has taken place, as in the ash from coal. It is often as porous as a sponge, and so light that it will float, as the *pumice* does.

These fragments are of all sizes, from bits the size of dust to huge stones, tons in weight. They may rise only a few feet or scores of feet, and fall back into the vent; or they may rise thousands of feet into the air, the largest falling near the vent, while smaller fragments may be drifted in the air currents for scores or even hundreds of miles before settling to the earth.

Bombs and Ash in the Air. — The explosive action of the included gases in molten lavas must be very great, for the temperature is far above 773° F., the *critical* point of water, that is, above the temperature at which water is always a gas, no matter what the pressure may be. It is sufficient to carry ash to a height of two or three miles in the air, and to hurl huge stones several miles. It is reported, for example, that a block weighing 200 tons was hurled a distance of 9 miles from the vent during an eruption of the volcano Cotopaxi in Ecuador. As the gases expand, while the fragments cool, they are not merely rendered porous, but are blown into bits. Fragments of volcanic dust that were collected 65 miles from Cotopaxi, whence they came, were found to be so small that from 4000 to 25,000 were required to weigh a grain. Such dust will float for a long time in the air, and it enters almost any cavity, no matter how small, sifting under windows, even entering into the interior of watches.

So great a quantity of ash and dust rises from a violent volcanic eruption that it completely obscures the sun for miles around. During the eruption of Coseguina in Nicaragua, in 1835, for example, darkness prevailed throughout a radius of 35 miles from the vent. Near the volcano there was a fall of ash which covered the ground to a depth of 10 feet, while volcanic dust fell four days later in Jamaica 700 miles distant. How great a quantity is expelled during a violent eruption may be inferred from the following estimates: the ash erupted in 1880 from Cotopaxi is estimated to have been fully 2,000,000 tons; nearly 5 cubic miles of ash fell during the eruption at Katmai, Alaska, in 1912; between 28 and 50 cubic miles of volcanic material is estimated to have come from the volcano Tomboro on the island of Sumbawa near Java in 1815, or an amount equal to one hundred and eighty-five mountains the size of Vesuvius.

Variations in Fragmental Material. — There is much difference in the matter of expulsion of volcanic fragments, according to the associated conditions. In a very liquid lava the gases rise and escape with little commotion, though now and then great bubbles may rise and throw up fragments of the lava. This result is quite certain to follow when the surface of the lava column cools to a pasty state, or when it becomes frozen over with a solid crust. In the Hawaiian volcanoes, for instance, clots of lava are thrown out, and, falling back around the vent, build small, steep-sided cones, to the sides of which the still plastic lava lumps cling as they fall.

Lapilli and Bombs. — Even in normally viscous lavas there is boiling and escape of steam bubbles from the surface of the lava column, but the explosive force of the included gases is much stronger than in the liquid lavas. Consequently, the lava is tossed higher in the air, and the fragments are more porous. In Vesuvius, for example, pieces of slag, lapilli, and volcanic bombs are thrown up, even during stages of comparative quiet; and they often fall to one side of the vent so that one does not venture near it. The *lapilli* are small fragments, as large as a pea or a nut, often rounded, but sometimes angular and usually porous. The term *slag* applies to porous fragments of various sizes and shapes, resembling furnace slag or cinders. *Volcanic bombs* are rounded, elliptical, or pear-shaped masses, varying in size from a few inches in diameter to several feet, and usually somewhat cellular inside. They were evidently hurled out while still in an unsolidified state, and gained their rounded form while whirling through the air and forming their solid crust. Sometimes they are flattened on one side, evidently by impact when they struck the ground before being quite solid; at other times they have been broken by falling. Very often they are cracked by fissures and planes developed by contraction during cooling.

Volcanic Ash and Tuff. — If a crust forms on the upper portion of a lava column, the rise of the included gases may be so checked that a great strain is applied, which ultimately may blow out the consolidated lava and even blow away a part of the cone. It is at such times that the most violent eruptions take place, and the imprisoned gases, rapidly expanding, throw the lava high in the air. As already stated, these gases disrupt the lava into bits of ash, sand, and dust, the coarsest of which fall back near the vent, while the finer particles drift far and wide.

The volcanic fragments that settle on and near volcanoes make deposits of various kinds from the coarse-textured lapilli, bombs, and slag to deposits of volcanic sand, ash, and dust. The latter sometimes forms extensive beds near volcanoes, known as volcanic *tuff*. Scattered through the deposits near the vent are oftentimes found fragments of non-volcanic rocks, such as limestone, schist, etc., evidently torn off by the ascending lava in its passage through the strata underlying the volcano in the early stages of its formation.

Volcanic Gases. — The vast quantities of steam which rise from volcanoes, as well as other phenomena associated with eruption, proved conclusively that there are great quantities of included gases, evidently dissolved in the molten magma, and consequently having the same temperature as the lava. Among these gases are the elements of water, — hydrogen and oxygen, — at a temperature far above the critical point of water (773° F.). Just what happens in the process of escape is unknown; but water vapour rises from lava flows, from the lava column in the vent, from the ash eruptions, and from cracks and crevices in the volcanic cone. During great eruptions prodigious quantities of steam rush out and form a great cloud, thousands of feet high, above the vent. It is estimated that during an eruption at Etna enough vapour escaped in a period of 100 days to form 462,000,000 gallons of water.

Rain following Eruptions. — Condensing as it rises, the vapour forms clouds and rain, and, therefore, much water falls back upon the volcano. There are copious rains, and thunder and lightning develop in the steam cloud, so that great volumes of water rush down the slopes, often causing great destruction in their path. These floods are sometimes augmented by the melting of snows or by the emptying of lakes.

Poisonous Gases. — Many other gases arise from volcanoes, including hydrochloric acid vapour, sulphurous acid, chlorine, oxygen, hydrogen, and carbon dioxide. It is highly probable that the oxygen and hydrogen exist uncombined in the lava, and that they unite on escape, giving rise to the explosions and to the great volume of steam that rises from the vents. Long after volcanic activity ceases, steam continues to rise from and near the vents; and carbon dioxide issues even after the steam ceases. Thus in the volcanic Eifel district of western Germany, long since extinct, carbon dioxide issues from a multitude of points, and many of the numerous acid springs there are due to this gas. Many medicinal and hot springs are due to the volcanic conditions, and may be interpreted as the last stages of expiring volcanic activity. Geysers are evidently the product of one stage in the dying out of vulcanism.

In some places so much carbon dioxide escapes from the earth that the air is locally charged with it, and animals may be suffocated by it. It is said that in former days birds flying over Lake Avernus, in a small crater on the Bay of Naples, were often suffocated by the noxious vapours; but this is not true to-day. In a small valley in the Yellowstone Park, however, bears are sometimes killed by the carbon dioxide that issues from the ground; tigers and deer are killed in the "Valley of Death" in Java, a deep hollow from which great quantities of carbon dioxide escape; and insects, birds, and mice are sometimes killed near the orifice whence carbon dioxide escapes along the shores of Laachen See, a lake in one of the extinct craters of the Eifel.

Mud Flows. — The rains that fall upon the volcanoes, finding loose ash freshly fallen on the steep slopes, wash it down in such quantities as often to form great flows of liquid mud, called *mud flows* or *mud lavas*. These are masses of pasty mud, sufficiently liquid to flow, yet not stiff enough to stand upon. They move with a velocity varying with the liquidity and the slope, and may cause even more destruction than lava itself. Everything in the path of such a mud flow is enveloped and overwhelmed, as was the case during the eruption of Vesuvius in the year 79 when a mud flow swept over Herculaneum, quickly covering and entering the houses, and sealing them effectively in a mass of mud which has since solidified. Similar mud flows descended the flanks of La Soufrière in the island of St. Vincent during the eruptions of 1902, and they were steaming hot, probably partly because of the heated rains, partly because of the hot ashes upon which they fell. From their surface jets of steam arose, and even minor eruptions occurred, erecting small cones on the surface of the mud flows.

The Volcanic Cone

The Building of Volcanic Cones. — A single eruption from an orifice builds up a mound-shaped deposit, or a *cone*, around the vent; and successive eruptions may so add to the cone as to make it a mountain of large size. Thus Vesuvius is 3880 feet high (Pl. VII); Etna is 10,870 feet; and Mauna Loa is 13,675, or, reckoned from its base beneath the sea, fully 30,500 feet high. So far as is known these volcanoes are composed entirely of lava or fragmental products, poured forth from within the earth during successive eruptions that have occurred during an unknown number of preceding centuries. There is, therefore, a vast amount of molten rock extruded from within the earth, even in a single volcano; and since great quantities have drifted away in the form of ash and dust, there is even more than the volcanic cone alone would indicate.

Lava Cones and Ash Cones. — The volcanic cone varies greatly in shape as well as in size, and one of the main causes for variation is the condition in which the molten rock is expelled. If the lava flows forth in streams, practically all that comes out remains near the vent, and, therefore, contributes toward the growth of the cone; but, if

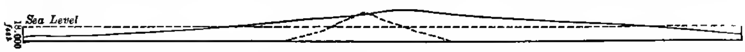


FIG. 297. — Contrasted profiles of a broad lava cone like one of the Hawaiian volcanoes and a steep ash cone like Vesuvius.

it is blown out in fragments, much may settle at a distance from the vent. A lava cone is, therefore, apt to be larger than an ash cone having an equal number of eruptions. The lava cone will, however, be less steep than the ash cone (Fig. 297); for while the ash settles and tends to assume the angle of slope of loose materials in the air, the lava tends to flow away from the vent. Lava will congeal on any slope, up to the vertical; but it is able to flow over the most gentle of slopes. Some of the liquid lavas of the Hawaiian Islands, for example, have flowed down slopes of less than 1°.

Ash cones often have a slope of from 30° to 40°, but of course denudation is always at work removing fragments from higher to lower points, and thus tending to flatten the slopes. Lava cones have a much more gentle slope; that of Mauna Loa, for example, having an average slope of only 6°. It is, therefore, a much less striking mountain than many a smaller, steeper cone. An additional reason for the broad and gently sloping lava cones is the fact that the eruptions commonly come from the flanks of the cone, and, therefore, can flow farther out than if they came from the summit of the cone. Most active volcanoes erupt both lava and ash, sometimes both together, sometimes one or the other. Such cones have slopes intermediate between the lava and ash types.

The Crater. — The crest of the volcanic cone is usually truncated, and in it is sunk a pit, or *crater*, whose diameter varies from a few hundred yards to a mile or more. Some very large craters, like that of Mauna Loa, which is about 8000 feet in diameter, are called *calderas*. Both the form and depth of the craters vary greatly according to the state of eruption; that of Vesuvius, for example, was several times larger after the eruption of 1906 than before it. The inner slope is commonly precipitous; and from its porous and rifted walls steam and other gases issue, while still greater volumes issue from the crater bottom.

Conditions within Craters. — During stages of inactivity, or after eruption is at an end, the crater bottom is covered over with solidified lava, fallen blocks, and scoriæ, through which, here and there, small fumaroles of steam arose. This was the condition of Vesuvius when the author saw it in March, 1910; but during a visit seven years earlier the crater bottom was in a far different state. Vast quantities of steam, sulphurous and other gases were pouring out, a fiery glow was visible through the steam cloud, and, now and then, it was lighted by the bursting forth of the imprisoned gases. Immediately followed detonations which shook the crater edge, the volume of steam increased, and masses of lava, some of them of large size and still glowing, were hurled above the crater edge.

Several descents have been made into the crater of Vesuvius (Pl. VII), notably by Cappello in 1911, by Malladra in 1912, and by Storz in 1913. Times of inactivity were chosen, but the dangers seem to have been less from poisonous gases than the falling of stones from the cooling and rapidly disintegrating crater walls. Temperatures of 200° F. were recorded in the air at the bottom of the crater, which was 984 feet deep in 1912. A thermometer lowered 200 feet into an opening in the bottom of the crater recorded a temperature of 1170° F. in December, 1913.

Volcanic Eruptions. — This circular pit is the opening of a vent, filled with molten rock forced upward from a reservoir at an unknown distance beneath the surface. Now and then the volcanic forces gather energy enough to propel the lava high in the air, and a destructive rain of ash, scoriæ, slag, and bombs falls upon the slopes of the cone; at the same time the tremendous strain of the rising lava and its included gases rends open the side of the cone, and lava flows out through one or more fissures. The volcano is in eruption.

In a few days the activity may cease, or eruption after eruption may occur through a period of weeks or months before there is sufficient relief to permit a period of quiet. After each eruption of this kind the mountain slopes are coated with freshly fallen fragments, as snow covers a land surface, and soon stream work begins its task of removing it, gullying the surface and bearing the loose fragments to lower levels. To prevent this, and to protect vineyards on the lower levels of Vesuvius from inundation of débris thus washed down, extensive retaining walls have been built since the 1906 eruption.

Parasitic Cones. — Where the lava outflowed, the side of the cone is scarred by a great black track of utter desolation, and at the point of outflow there is, perhaps, a small cone built up. Such secondary cones on the flanks of a volcano are called *parasitic cones*, of which there are 200 on the slopes of Etna, some of them 700 feet high.

Slopes of Volcanoes. — Besides these features there are on the slopes of volcanoes, as on all land forms, the excavations made by running water. In an active volcano, however, this denudation is frequently interfered with, and the valleys often completely blotted out by the falling ash, or by mud flows, or by lava flows, which normally enter the valleys as they pour down the slope.

Destruction of Volcanic Cones from Within. — It is by such processes that the volcanic cone usually grows; but it is sometimes subjected to conditions which interfere with the development of the normal, symmetrical cone. In some cases, the withdrawal of the lava from beneath the cone permits collapse, and a truncated cone is produced with a huge caldera, like that of Crater Lake in Oregon. In other cases, after a period of inactivity, a great explosion occurs, which blows away the top of the cone, also causing a huge caldera, or, as in the case of Krakatoa in the Straits of Sunda, blowing away one side of the cone and leaving the other part standing. Subsequent eruptions may build a new cone in the caldera, or on the site of the wrecked cone, and partially repair the damage of an earlier explosion. This has been the case in Vesuvius, where Monte Somma, a part of the old crater rim that stood before the eruption of 79, still remains on one side of the present cone. Double vents and overlapping craters are not uncommon, as on Mount Shasta, but one is always younger than the other and continues activity longer.

Active, Dormant, and Extinct Volcanoes. — It is very common to class volcanoes as active, dormant, and extinct, though the three kinds grade so into one another that there can be no hard-and-fast line drawn between them. A truly active volcano cannot be mistaken, for, even though it may be temporarily quiescent, there is clear evidence of recent activity; and the presence of slumbering energy is plainly shown by the steam that issues from its crater or slopes. On the other extreme, a volcano may be so certainly extinct that one cannot fail to recognize the fact. Even though the cone, with its crater, may still remain, it no longer emits steam, though carbon dioxide may still rise from it. Such is the condition of the volcanoes of the Eifel district of western Germany; of the Auvergne in central France; and of a multitude of volcanoes in western United States.

Between these two extremes, however, is a condition of quiescence which may be either temporary or permanent, and it is quite impossible to state which. Doubtless Vesuvius before its eruption of 79 was in a condition which would warrant the assumption that it was extinct, but we know that, after centuries of quiet, it broke forth in the most terrible eruption that it has experienced within historic times. Ever since, it has been intermittently active, though at one time, from 1500 to 1631, it was dormant for a period of 131 years. Even centuries of inactivity do not necessarily prove extinction.

Some volcanoes are in a state of almost incessant activity, but most of them are intermittent, the periods of inactivity varying in length, and the intervals usually being irregular. When the period of quiet has been long and the dormant volcano breaks into activity, the eruption is apt to be of exceptional violence, for during the period of quiet, the lava in the vent has solidified and given rise to an obstacle which only a great explosion can remove.

Specific Instances of Volcanic Eruptions

It is clear that while there are certain features in common among volcanoes, there are also marked differences. A fuller understanding of these differences may best be gained from a brief description of a few typical volcanoes and their eruptive activity.

Italian Volcanoes

Present and Former Volcanoes in Italy. — There is a chain of volcanoes extending almost the entire length of the Italian peninsula, from near the base of the Alps to Vesuvius, then continuing southward through Lipari Islands to Sicily, and to the Mediterranean south of that island. North of Vesuvius the volcanoes are extinct, though some of them have been active in recent geological times; their cones are still quite perfect, and their craters are unbreached, and occupied by lakes, like Lake Nemi near Rome. On the Bay of Naples there is a group of volcanoes that have been active during historic times, including Vesuvius; south of it is another group in the Lipari Islands; on Sicily is Etna; and south of it there has also been eruptive activity.

Lipari Islands. — This small group of islands, north of Etna and between it and Vesuvius, consists of a series of seven large and a number of small volcanic islands. Several of these are apparently extinct, though rising vapours, hot springs, and the cones and craters testify to recent activity. Vulcano has a crater over 500 yards across, from which steam constantly rises and explosive eruptions occasionally take place. At the north end of the island is the small Vulcanello, which was upheaved from beneath the sea in the year 200 B.C. and is now connected with the main island. It has three overlapping craters, each evidently due to an eruption from a slightly different vent, caused by the closing of the earlier vent between eruptions.

The northern island, Stromboli, sometimes called "the lighthouse of the Mediterranean," is remarkable for the fact that it is in a constant state of activity, usually of a very moderate character. The cone itself rises about 3000 feet above the sea, but including the portion beneath the sea it is about a mile high. On the northern side of the summit, and about 1000 feet below it, is the active crater, from which steam, often called " smoke," is constantly rising. In the bottom of the crater, lava may be seen, and at intervals of from 3 or 4 to 10 minutes it swells up in a blister and is exploded by the rising gases, much like boiling oatmeal. With the explosion, which may generally be safely watched from the crater edge, a shower of hot stones is thrown up to a height of several hundred feet. Stromboli has been in similar constant activity throughout historic times. There has, however, been variation in intensity of eruption, and there is a belief among the fishermen that the amount of steam and the force of eruptive activity vary with the weather, so that it can be used as a kind of barometer. This is not at all improbable, since the eruptive activity is apparently in such delicate balance with atmospheric pressure that a diminution in pressure, such as accompanies a storm, may easily induce a more copious discharge of the included gases.

Graham Island. — Between Sicily and Africa lies the extinct volcano of Pantellaria. About halfway between it and the coast of Sicily, and 30 miles distant from Sicily, a submarine eruption occurred in 1831, preceded by earthquake shocks felt at sea and on the coast of Sicily. About July 10 a column of water was seen to rise 60 feet in the air, followed by a column of dense steam rising 1800 feet. On July 18 there was a small island 12 feet high with a crater in its centre, from which volcanic ejecta were being thrown, accompanied by great volumes of steam. By August 4 the new island had a circumference of three miles and rose to a height of 200 feet at a point where, before, there had been 600 feet of water. Before the end of the year the island had disappeared, doubtless by wave attack upon the loose ash.

The Graham Island eruption illustrates a very common type of volcanic action. From a vent, usually not far from a centre of volcanic activity, enough material is erupted in a brief interval of time to build a cone of considerable size; then follows inactivity, and the cone is left to the attacks of denudation. Such cones abound on the slopes of large volcanoes, as on Etna, and near the base of such cones as Vesuvius. Many of them have been seen to form on the land, and tens of thousands of others have been formed without human witness or record. Doubtless they are common in volcanic regions in the ocean, for already a number have been seen to form, as Graham Island was.

In the ocean such small cones of loose ash, if they rise to the surface, fall ready prey to the wave attack, as we have seen; their sites are marked only by shoals. On the land they are far more permanent, for on such small cones large streams cannot develop, and, in such porous deposits, there is so much percolation that the erosive action of running water is greatly reduced. Accordingly such cones long retain their perfect form, giving rise to a deceptive appearance of extreme recency of origin.

Etna. — This beautiful, symmetrical cone, rising from the sea level to a height of 10,870 feet, is the loftiest volcano in Europe. Its base is almost circular, and is about 87 miles in circumference. Etna presents a complete contrast to Graham Island, for here eruptive activity has persisted through a long series of centuries, and a huge mountain has been built up by the ash and lava erupted from within. The first eruption of which we know occurred in the year 476 B.C., and there is record of at least 80 vigorous eruptions since that time. During the nineteenth century there have been about 20 eruptions, or an average of one every four or five years. These eruptions vary greatly in violence, in the interval separating them, and in the length of time they last. During some of the eruptions the volcano is active for two months or more, with repeated explosion and lava flows; and in the interval between eruptions a column of steam ordinarily rises from the summit crater.

The violent eruptions are commonly preceded and accompanied by earthquakes, some of which have been very destructive. For example, in connection with the eruption of 1693 between 60,000 and 100,000 lives were destroyed by earthquakes. During the eruption successive explosions send vast columns of steam and ash into the air from the summit crater, while one or more fissures open on the flanks of the cone, from which floods of lava escape, flowing down the slopes at first rapidly, then, as it solidifies, with increasing slowness. These lava flows escape from all sides of the cone, and at various levels, most of them ceasing to flow before reaching the mountain base, though some spread out at its base, and even enter the sea.

Over the fissure from which the lava issues, parasitic cones may be reared. This habit of the breaking out of lava from the flanks of volcanoes is a common phenomenon of volcanic eruption. It is evidently due to the great strain exerted upon the flanks of the cone by the column of imprisoned lava. The very weight of the column exerts a pressure of from 70 to 80 tons per square foot for every thousand feet of lava in the column. Added to this is the great pressure of the included gases, whose explosive force is clearly indicated by the prodigious height to which it expels rock fragments from the crater. Doubtless also the sides of the cone are weakened by the jarring and shaking accompanying eruption; and possibly there is also an influence from the melting of the rocks along the conduit.

It seems evident that a volcanic cone can be built higher than the lava column can rise in its conduit. The upper part of the cone, being made largely of fragmental ejecta, cannot resist the pressure upon it, and therefore the lava drains out through fissures, not by overflow of the crater rim. There may be other factors involved, such as the failure of the force that is pushing the lava upward to raise it to the crater rim, but here and elsewhere the weakness of the upper cone is evidently the main cause for the lateral eruptions.

When eruption through the fissures ceases, they are filled with molten rock, which, on cooling, forms vertical or highly inclined seams or dikes of rock more solid than the fragmental layers. These tend to rivet the layers together, and thus strengthen the cone; it is conceivable that they might finally so strengthen the walls as to check further fissuring. Where volcanic cones have been disrupted by explosion, and where extinct cones have been dissected by denudation, the dikes in former fissures are clearly exhibited, extending in various directions.

One of the greatest eruptions of Etna was that of 1669, which was preceded by a violent earthquake. Six parallel fissures opened, one after the other, one of them 12 miles long and extending to within a mile of the summit of the cone. Near Nicolosi, which had been destroyed by the earthquake, a double cone was formed of scoriæ, rising to a height of about 450 feet. The lava that issued from the mountain side flowed 13 miles the first twenty days, or at the average rate of 162 feet per hour; but twenty-three days were required for it to flow the last two miles, or at a rate of but 22 feet per hour. It entered the sea with a current 600 yards broad and 20 feet deep, pushing the coast outward. In its course this lava flow overwhelmed fourteen towns and villages, and finally reached the walls of Catania on the coast. It slowly rose and, falling over a wall 60 feet high, covered part of the city; but it stopped its forward movement there. This lava flow still forms a terrace on one side of Catania, and houses and streets are built upon it.

Etna had severe eruptions in 1910 and 1911, in the latter year pouring forth more lava in 5 days than in the 26 days of the 1910 eruption. Scores of vents opened on the sides of the mountain and the main crater ejected ash which buried the adjacent country to a depth of several inches.

The lava flows of recent date are readily distinguished on the flanks of Etna, and in general they are identified by the different degrees of disintegration and vegetation cover. The most recent are great, black bands of rough-surfaced lava, wholly uninhabited and utterly desolate in appearance; but the more ancient ones have a soil on which the vine and other cultivated plants are raised, in some cases merely in pockets where rough fragments have accumulated, or to which soil has been carried by the peasants. Some of the lavas of the past century are now in part covered by vegetation; but on the other hand a period of over 500 years has not sufficed to clothe the flows of 1381 with vegetation.

Etna is a perfect type of a symmetrical volcanic cone erupting both ash and lava. The symmetry of its form is interrupted by the parasitic cones already mentioned; but, though these are conspicuous features in the detail of the landscape, they are lost in a general view of the cone as a whole. The symmetry of the cone is also somewhat modified by the presence of a great depression, or valley, known as the Val del Bove, evidently the product of some catastrophic, prehistoric eruption. With the copious outflow of lava from the flanks of the cone, it is being broadened at the base. Like all volcanoes it is gullied by erosion, but the successive lava flows tend to seal up these valleys before time enough has elapsed for them to progress far in the cycle of denudation.

The Bay of Naples. — The northern side of the Bay of Naples is volcanic in character, with Vesuvius on one end, the volcanic island of Ischia on the other, and a group of small cones between. Some of these are small islands, others are on the land, in what is known as the Phlegræan Fields. This region was the seat of the earliest Greek civilization in Italy; it was later of importance in the days of the Roman Empire; and the shores of the Bay of Naples are to-day densely settled.

Ischia and the Phlegræan Fields. — Ischia, an island 19 miles in circumference, is entirely volcanic, and there are a number of small cones and craters upon it in addition to the main cone, Mount Epomeo, 2782 feet high. It is generally believed to have been quiet for 17 centuries; but before the Christian era this volcano was active, the island being deserted by the Greek inhabitants because of the great eruptions of 474 B.C. Another eruption occurred in the year 92 B.C., and there were other eruptions before and after this. The last eruption, however, was in 1302, and since then the volcano seems to have become extinct, though there are occasional earthquakes, like that of 1883, which destroyed Casamicciola. This may indicate that the volcanic forces are merely slumbering.

In the Phlegræan Fields the numerous low cones and craters are evidently all of recent origin. Among them are two known to have originated within historic times. The first of these is Solfatara, which erupted in 1198, but is known to have existed before. Steam still rises from the floor of its crater in great jets, and sulphurous gases are depositing sulphur crystals around the orifices of the multitude of smaller steam jets.

Monte Nuovo. — Near by is Monte Nuovo, a circular cone 8000 feet in circumference and about 440 feet high, rising from the shores of the bay. It is truncated on the top and contains a perfect crater. Before 1538 the site of this cone is said to have been a lake and for two years the region was visited by frequent earthquakes. On the 28th of September, 1538, there were twenty earthquake shocks, and on the 29th, the ground was rent and showers of hot stones and ashes were thrown into the air, and the cone was speedily built before the eyes of the horrified observers. Other accounts of this eruption differ from this one in minor details. To-day the slopes of the cone are terraced and occupied by vineyards.

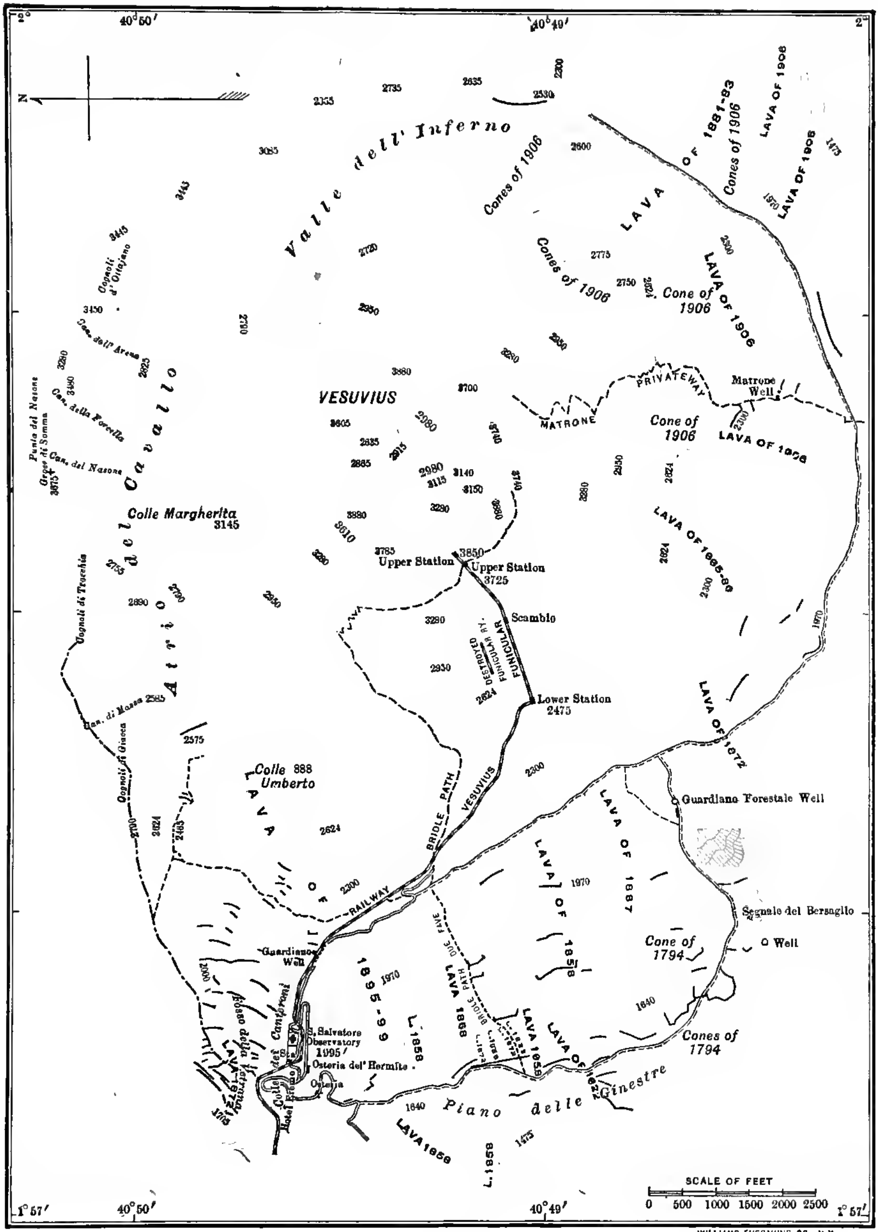
Vesuvius. — It is Vesuvius, however, that forms the central point of interest in this volcanic district (Pl. VII). Up to the year 79 A.D. it had been in a long period of repose. There is every reason to believe that, during the centuries of Greek and Roman occupation of the region, it had not been active. It was a low, broad cone, with a great crater, or caldera, at its summit, some three miles in diameter. Woods covered the rugged slopes and crater walls, cultivated farms dotted the lower mountain side, while villages and cities skirted its base then as to-day. Among these were the populous cities of Pompeii and Herculaneum.

In the year 63 there was a destructive earthquake, which did damage in Pompeii that had not been fully repaired when that city was de-

Fig. 298. — A street in Pompeii.

stroyed in 79. Other shocks followed, becoming more and more numerous and violent in August of the year 79; then came the most violent eruption that Vesuvius has experienced in historic time. One side of the crater wall was blown away, and a cone was started on its site, from which eruptions have occurred at intervals ever since; the other part of the crater wall, called Monte Somma, still rises on the north side of the cone. It is made of volcanic ejecta and is riven by numerous dikes, and is separated from the present day cone by a crescentic valley which neither ash nor lava have as yet succeeded in completely filling.

Ashes fell upon the surrounding country, a huge column of steam and ash darkened the sky, and great torrents of water fell upon the flanks of the mountains. Pompeii was buried beneath a cover of ash and dust, which penetrated every crevice and so sealed the objects in



VESUVIUS

The upper part of the cone of the active volcano, Vesuvius, with lava flows of various periods dated. Old wall of Monte Sonnsa on the north. Combined contour and hachure map. Elevations in feet. (After Friedlaender in Petermanns Mitteilunger, 1912.)

a compact cover. In the excavations which have been made during the last century, objects of even a perishable nature have been recovered. From them we are able to tell far more about the life and habits of the people of that day than history alone tells. It is a wonderful experience to walk through the deserted streets of this ancient city of 20,000 inhabitants (Fig. 298), to realize under what terrible conditions the people were driven out or overwhelmed in their efforts to escape. It is even more wonderful to examine in the museums the perfectly preserved pictures, utensils, and other objects hurriedly left behind by a terrified people fleeing before one of the most frightful catastrophes of history. A contemporary account of this eruption, from the letters of the younger Pliny to Tacitus, has been translated by Shaler.

Herculaneum was overwhelmed by a great mud flow, and this has since been covered by a lava flow, on which a village now stands above buried Herculaneum. Part of it is now exposed to the air, but it has been more difficult to excavate this city, and it has been only partly explored by subterranean excavations, whereas Pompeii is largely opened to air by the removal of the cover of from 10 to 30 feet of loose volcanic ash, lapilli, sand, and dust. Doubtless other houses and villages, destroyed during that great eruption, lie buried beneath the accumulation of ash, lava, and mud flows that were thrown out in 79 and subsequent eruptions.

The record of the activity of Vesuvius after the eruption of 79 is incomplete, but there is record of eight eruptions before 1138, after which there was quiet for 168 years; but during this interval there was an eruption of Solfatara in 1198 and of Ischia in 1302. Vesuvius erupted again in 1306, and in 1500, after which the volcano remained dormant until 1631, though in the interval Monte Nuovo was formed. Between 1138 and 1631, an interval of 493 years, there is no record of vigorous eruption of Vesuvius. This period of tranquillity was interrupted by the second most violent eruption of Vesuvius in 1631, during which vast quantities of ash were expelled, while seven lava streams poured down the slope, one of which overflowed the site of Herculaneum, destroying a village built there, while others overwhelmed other villages at the mountain base. Since that time Vesuvius has been frequently active, and ten years has rarely elapsed without an eruption, while in the interval the crater has been steaming, and usually scoriæ have been emitted as described on p. 443.

The last two violent eruptions occurred in 1872 and in 1906. The former began in January, 1871, with ejections from the crater and small lava streams from the sides of the cone. This period of activity culminated in the great eruption of April 24 to 30, 1872, during which vast quantities of ash were thrown high in the air, and numerous lava streams issued from fissures in the mountain side (Fig. 299).

The eruption of 1906 was similar in character, commencing nearly a year earlier and culminating in a period of grand eruptions between the 4th and 7th of April, 1906. It is estimated that the volcanic dust and steam were shot up to a height of 4 miles. It settled on the surrounding country, even in Naples, 10 miles distant, in sufficient quantities to cause the roofs to collapse. The mountain side was covered with ash, as with freshly fallen snow, and vineyards and orchards were badly damaged, while the roofs of houses collapsed under the unaccustomed load. In places four or five feet of ash fell on the surface. Four years later, when the author visited the volcano, the coat of ash was still notable, though it was evidently being rapidly removed by running water.

Lava issued from several fissures on the slopes of the volcano, coming apparently from near the site of the ancient crater rim of

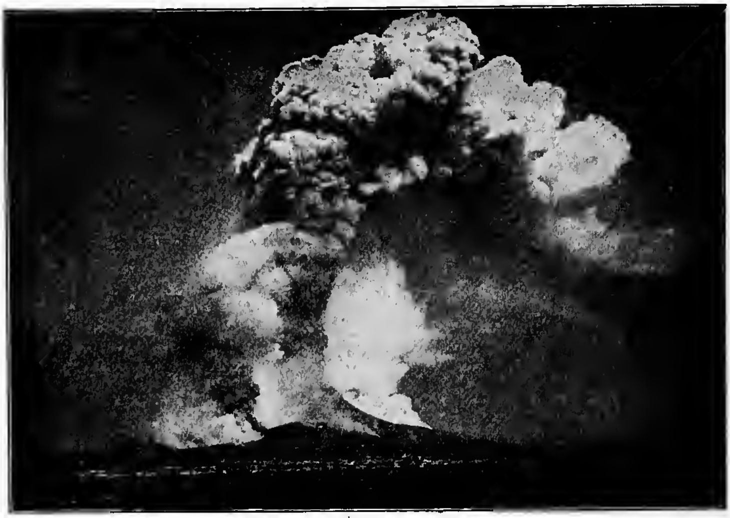


FIG. 299. — Vesuvius in eruption in 1872.

Monte Sommà, blown away in the eruption of 79. It flowed down the slope of the cone in narrow streams, one of which invaded the village of Boscotrecase, overwhelming a part of it, but stopping short of complete destruction.

Thus Vesuvius resembles Etna in the nature of its eruptions; but the cone is far smaller than that of Etna, and a less volume of lava is erupted. There are a few small parasitic cones on Vesuvius, called *bocas*. They form no such conspicuous feature as do those on Etna. The most noteworthy feature of the Vesuvian history is the long intervals of quiet, during which the volcano might be thought to be extinct, then the sudden awakening with an explosion of terrific violence, removing the obstruction caused by the solidification of the

Fig. 300. — Caldera in the Eifel district with cultivated fields upon inner slopes.

lava in the vent, and with it a part of the former crater. Even the eruption of 1906 completely altered the upper part of Vesuvius, lowering its summit by some 500 feet, truncating its top, and forming a far larger crater than existed before. In the intervals of quiet other neighbouring vents were active; but in the past three centuries of practically incessant activity of Vesuvius there have been no eruptions from other neighbouring vents.

Other Volcanoes in Europe

Volcanoes of the Eifel. — In Germany there are no active volcanoes to-day; yet in former days there has been much such activity, notably in the district of the middle Rhine and west of this in

Fig. 301. — Volcanic necks in the Auvergne district of France.

the volcanic Eifel. Some of the rocks exposed in the gorge of the Rhine are lavas, and there have been successive periods of activity, during which different types of lava were erupted.

The latest phase of vulcanicity in this region occurred in the Eifel; and the perfection of the cones and craters, their relation to the topography of the country, and the emanations of carbon dioxide and other gases, prove conclusively that the period of activity was very recent. But, so far as can be told, the period of vulcanism is, for the present at least, at an end in this district.

Many of the Eifel volcanoes were the result of a single explosion, while others had successive explosions, and from some lava streamed forth. Some of the cones are very small and none of them are of that large size which results from centuries of activity. In some cases no noticeable cone was formed — only a crater-like cavity now occupied by one of the circular lakes or *maare* (Fig. 300). Similar lakes also lie in the craters of some of the cones. While most of the eruptions consisted of ash, there were some which threw out no ash or lapilli, but only fragments of the country rock. These were merely steam eruptions, without the accompaniment either of lava or volcanic fragments. Throughout the region blocks and pieces of country rock occur in the ash deposits, indicating that the rising mass drilled its way through the upper crust and carried the fragments with it. Among these blocks are pieces of granite and other rocks not found in place in the region, but evidently lying at a considerable depth below the surface, in the portion of the earth's crust through which the lava was forced.

Auvergne and Other Regions. — Another region of recently extinct volcanoes in Europe is in the Auvergne region of the highlands of central France (Fig. 301). Earlier eruptions occurred also in Scotland, Ireland, England, and many other parts of Europe not now volcanic.

Pelé in the Island of Martinique

The Lesser Antilles, which border the Caribbean Sea on the east, are a chain of volcanic cones, rising from a submarine mountain ridge, which sweeps down to the South American coast. One of these islands, Martinique, contains the cone of Mont Pelé, in which, prior to 1902, there was a crater some 2000 feet deep and half a mile in diameter. The volcano was breached by a deep gash on the southwest side, opening toward St. Pierre, the capital of the island, a city of about 26,000 inhabitants (Fig. 302).

There had been no eruption of this volcano since 1851, when there was an outbreak that did little damage; but in April, 1902, signs of activity appeared, vents opening in the crater bottom, and steam and ashes being thrown out of the crater. Sulphurous vapours poured out of the mountain, ash fell in St. Pierre, and frequent earthquakes occurred, among other things breaking the cables offshore. In the early days of May there was considerable activity, but on the 8th a terrific eruption occurred, and the steam and ash rose high in the air; but a portion was propelled through the gash in the crater rim, and rushed down upon the city of St. Pierre with terrific force, going the distance of three miles, it is estimated, in about two minutes. The hurricane of superheated steam and hot ash overthrew buildings, hurled an iron statue from its pedestal, and overturned cannons. At the same moment the city caught fire, either from the hot gases or from the red-hot ash (Fig. 303). With a single exception the entire population of the city was instantly killed, for the cloud is estimated to have had a temperature of 1400° or 1500° F. and to have consisted of steam, sulphurous and other gases, and hot dust and other volcanic fragments.

Other eruptions took place during the succeeding months, some of them extending the destruction, and during their greatest activity it is estimated that the column of steam and ashes rose to heights as great as seven miles. By these eruptions a cone of volcanic fragments has been built up in the old crater, even rising above its former walls.

In the late stages of the eruption a peculiar phenomenon appeared in the form of a " spine " that slowly rose out of the crater. As it rose it crumbled away on the face, but more followed, though ultimately it collapsed. This spine consisted of hot, porous lava, apparently pushed up from the vent by the expansive force below. Its rise has been compared to the movement of a cork forced out of a bottle by the gases within (Fig. 304).

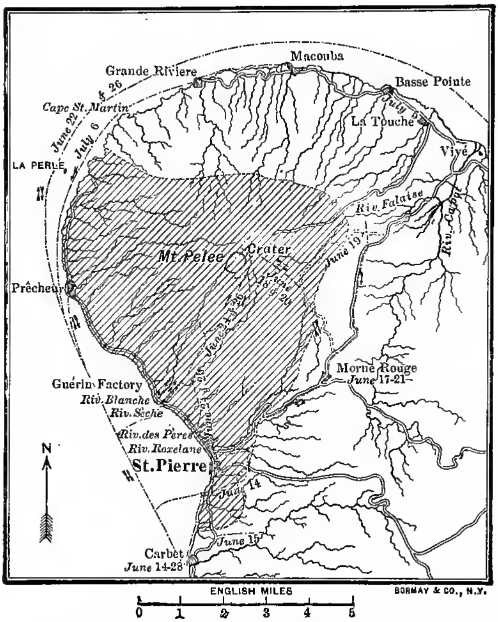


FIG. 302. — Zone of destruction (oblique lines) on the island of Martinique in 1902.

During the eruption of Pelé the volcano Soufrière in the adjacent island of St. Vincent also broke forth, as if in sympathetic activity; but with far less dramatic results. Ash from this eruption also spread over a wide area, devastating much of the surrounding country and settling on the sea round about, but especially in the direction of the prevailing winds. Great mud flows swept down the valleys, especially in St. Vincent, and from their surfaces jets of steam rose as they flowed along.

Both of these eruptions are of the explosive type, following long periods of quiet. They differ from the ordinary eruptions of Etna and Vesuvius in the absence of associated lava flows. The appalling destruction of life at St. Pierre was due less to the violence of the eruption than to the peculiar topographic feature which directed the blast upon the fated city. It has been compared to a break in the breach of a gun by which a part of the discharge escapes through the break instead of through the muzzle. Doubtless the lateral motion through

FIG. 393. — Ruins of the city of St. Pierre, destroyed in the eruption of 1902.

the gash was brought about by the overlying column of steam and ash. Such a phenomenon gives basis for understanding the enormous

FIG. 304. — The spine protruded from Mt. Pelé. (Heilprin.)

lateral pressure to which the walls of the volcanic vent are subjected by the vapour-charged lavas within them; and to account for the frequent fissuring of volcanic cones.

Krakatoa

This volcano, in the Straits of Sunda between the islands of Java and Sumatra, was in 1883 the seat of one of the most violent eruptions of which there is record. There was an eruption about a century earlier, and in the interval there had been such a solidification of lava in the vent, and such a gathering of subterranean energy that, when the eruption finally occurred, it took the form of a terrific explosion. There had been preliminary earthquakes and minor explosions, but, on the 27th of August, two-thirds of the island was blown into the air, and, with it and following it, vast volumes of steam and volcanic fragments. It is estimated that over a cubic mile of rock fragments was hurled upward during this explosion; and on the site of the cone the water was 1000 feet deep after the eruption (Fig. 305). The steam and volcanic dust is estimated to have been thrown 17 miles or more into the air.

Such a vast explosion naturally set a series of air waves in motion. Windows were broken at a distance of 100 miles, loud detonations were heard at a distance of 150 miles, and the sound was even heard in Australia 2000 miles away. A barometrical disturbance, moving at the rate of 700 miles an hour, passed through the atmosphere, and was recorded in the self-registering barometers, from the records of

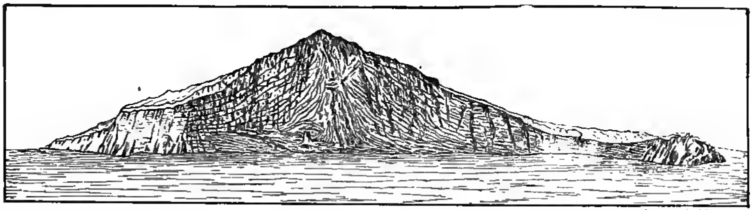


FIG. 305. — Cross-section of the half of Krakatoa left after the explosive eruption of 1883. (Symons.)

which it is believed that the wave which moved westward made the circuit of the earth three and three-quarters times, 82,200 miles, before finally becoming imperceptible.

The sea was also greatly disturbed, and waves rose more than 100 feet above tide level on neighbouring coasts. These water waves spread throughout the Indian and Pacific oceans, having been recorded on the tide gauges even as far distant as South Africa, 5450 miles from Krakatoa. These waves travelled at the rate of 467 miles an hour.

The falling ash and pumice covered the neighbouring sea as with ice, interfering with navigation, and doubtless it was drifted all over the surrounding oceans, slowly becoming water-logged and settling to the bottom, where not washed upon the coasts. The great volume of dust in the air darkened the sky at a distance of 150 miles; and some of the finely commuted particles evidently remained in suspension in the air for months, and drifted to various parts of Asia, Europe, and America. This conclusion is based upon the fact that a series of such unusually brilliant sunsets appeared progressively as to attract attention of observers in many places in each of these continents. A study of the records of the phenomena of the sunsets has led to the conclusion that they were due to the abundance of dust from the Krakatoa eruption.

On the remnant of Krakatoa every vestige of life was destroyed by the eruption, and had it occurred in a settled region, such as the country round about Vesuvius, the destruction of human life would have been appalling. As it was, the water waves were the main cause for the loss of human life. By them over 36,000 people were killed on the neighbouring coasts, and many towns and villlages were destroyed.

HAWAIIAN VOLCANOES

Very different is the volcanic activity of the active cones in the Hawaiian Islands, a chain of volcanic peaks on the crest of a submarine mountain ridge. There have been no less than fifteen large, active volcanoes in this chain, but only two are now active, — Mauna Loa and Kilauea in the largest of the islands, Hawaii. This large island is a volcanic pile, so far as known composed almost entirely of volcanic materials, mainly lava. It rises from the sea bottom at a depth of about 16,000 feet and extends nearly 14,000 feet above sea level, making a great volcanic mass 30,000 feet or more in height, forming, so far as known, the largest volcanic mountain in the world. It is not, however, built around a single volcanic vent, for it is made up mainly of three volcanic mountains, Mauna Kea, Mauna Loa, and Hualalai. The last of these has not been in eruption since 1801. Kea is now extinct, but Loa is in frequent eruption; and on its slopes, 20 miles from the summit and nearly 10,000 feet below it, is Kilauea, which projects only about 300 feet above the surrounding surface and hardly interrupts the long, gentle slope of Mauna Loa (Figs. 306, 307).

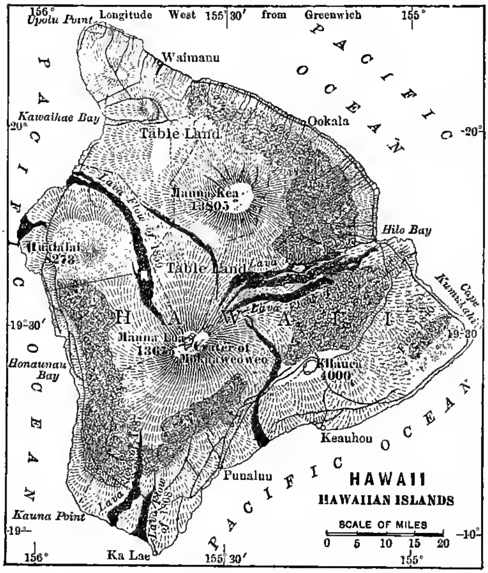


FIG. 306. — Map of the island of Hawaii, with dates of some of the lava flows.

In each of these volcanoes there is a large crater, or caldera, that of Mauna Loa being over three miles long and nearly two miles broad, while the Kilauea crater is about two miles long and one mile broad. Lava rises in these craters, not to be expelled by violent explosion, nor usually to flow out of the crater, but ordinarily to find escape through fissures on the mountain side, some from near the summit, others from far down the slopes. When the fissures open, there are sometimes earthquakes, though not always, and the liquid lava spouts out fountain-like, rising several hundred feet in the air, and flowing down the mountain side. Some of these flows are from 20 to 40

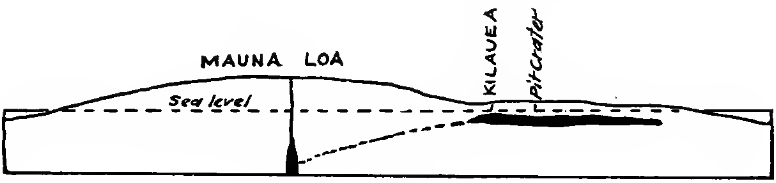


FIG. 307. — Relationship of Kilauea to Mauna Loa. (Daly.)

miles long, and some of them end only when they reach the sea and build the coast outward into the ocean.

There is no regular periodicity of eruption, but on the average there is eruption once in eight or nine years, this being apparently the time required for the lava column to rise in the vent and exert

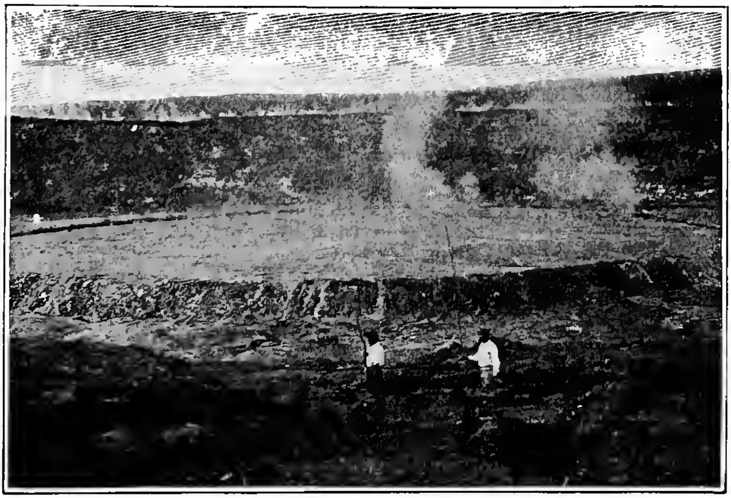


FIG. 308. — View within the crater of Kilauea, Hawaii (Pavlow).

the necessary pressure to burst through the side of the volcano. It is a remarkable fact that Kilauea shows no sympathetic response to conditions in Loa, and that lava stands in the crater of Kilauea, although it is several thousand feet lower than the lava column of the neighbouring volcano.

The crater of Kilauea presents a remarkable spectacle. It is a broad, deep pit bordered by black, terraced, lava walls. In the bottom is a rough plain of lava, crusted over for the most part, but with one or more lakes of liquid lava called Lakes of Fire, whose boundaries and position shift from time to time. In these lava lakes the molten rock is in a state of ebullition, and it boils and surges against the enclosing walls (Fig. 309), and sometimes overflows a part of the enclosing rim. From the surface fountain-like jets of molten rock rise two or three hundred feet in the air, and some-

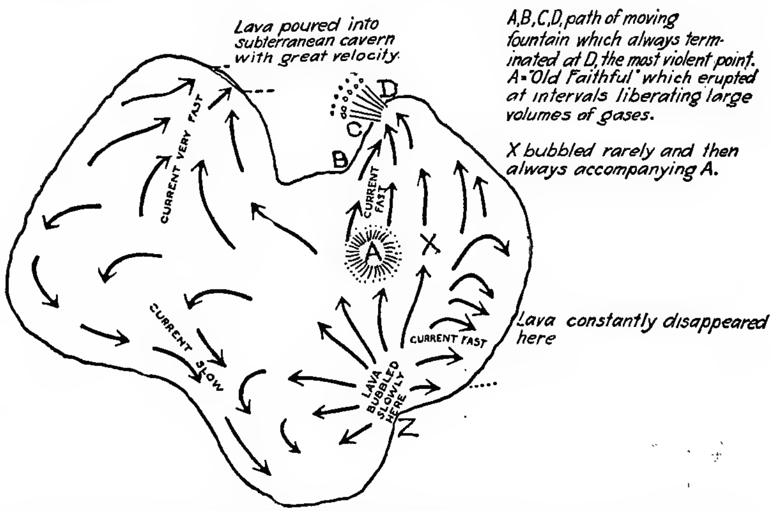


FIG. 309. — Sketch map of Halemaumau, in the crater of Kilauea, Hawaii, on Feb. 15, 1909. (C. H. Hitchcock.)

times the wind spins from it hair-like threads of natural glass known as Pelé's Hair.

The Hawaiian volcanoes differ greatly from any of those previously described. They are, in the first place, flat in slope, rarely sloping more than 6° or 8°; they are very broad, thus including a vast amount of volcanic material. While there is some ash and there are some lapilli, bombs, and other fragmental ejecta, the volcanoes are made mainly of successive lava flows. The lava outflows in a very liquid state, and with a tranquillity quite unusual in volcanic eruptions. Finally, one may watch the eruption, even from near at hand, with comparative safety; and one may go, not only to the crater's edge, but even down in it and to the very margin of the lava lakes (Fig. 308). It is a remarkable phase of volcanic activity.

Icelandic Volcanoes

Iceland is a volcanic island, consisting of an extensive lava plateau built during the preceding geological period from fissure eruptions. On this island is the large volcanic cone called Mt. Hekla. Iceland is of special interest because of the fact that there has been a continuation of fissure eruption into the historic period, the only known case of a phase of eruption once common. The great Icelandic eruption of 1783 was preceded by a submarine eruption 200 miles away some four months earlier. The lava came from a great fissure 12 miles long. It flowed out in both directions, extending 45 or 50 miles on each side with an average depth of 100 feet. River gorges were filled, and alluvial plains were flooded by lava lakes from 12 to 15 miles wide. There was, in fact, a literal deluge of lava, in which more molten rock flowed forth than in any case on record, a bulk estimated to exceed that of Mont Blanc.

Ash was thrown into the air from vents, and it fell not only on the island, but on the surrounding sea. Vessels between the Orkney and Shetland islands were obliged to shovel it from their decks; and so much fell in Caithness, in northern Scotland, 600 miles distant, that crops were destroyed. In Iceland, with a scattered population of but 50,000, fully 9000 people perished from inundations of water, caused by floods where streams were dammed and diverted; from the advance of lava; from poisonous gases; and from showers of ashes. The latter cause brought about famine by killing the cattle, by destroying crops and pasturage, and by the effect of the glassy volcanic dust, which clung to the grass that the cattle ate.

Other Volcanoes

Besides these there are a multitude of other active volcanoes which illustrate similar eruptive phenomena. In the Atlantic Ocean there is a chain of volcanoes forming the Azores, including some good-sized cones now extinct, and a multitude of small cones. That the volcanic activity has not quite died out here is indicated by the fact there have been several small eruptions during the past century. The Madeira, Canary, and Cape Verde islands are also volcanic, as are Ascension, St. Helena, and other islands farther south. The multitude of small islands and groups of islands in the Indian and Pacific oceans are also volcanic, or else coral islands built on volcanic cones, as are the Bermuda Islands in the Atlantic. Some of these are active, but most are now extinct.

There are volcanoes in the eastern Mediterranean, and in western Asia, including Mount Ararat, which was in eruption in 1840. The East Indies include a multitude of volcanoes, some of them, notably those of Java, having had violent eruptions. The same is true of the Philippine Islands, where the Taal volcano had a destructive eruption in 1911, and Japan, where Fujiyama is well known for its symmetrical cone (Fig. 310). The Sakurajima volcano had two great lava flows and ash showers, and destroyed 24 lives in January, 1914.

In the New World there is a nearly continuous chain of volcanoes from the Aleutian Islands to Chile. Many of these are extinct, especially those of western United States, but in the Andes and in central America and southern Mexico there are many active volcanoes.

In Alaska there are said to be no less than 57 active volcanoes in the Aleutian Islands, which extend westward about 1600 miles. Mount Wrangell on the mainland is the easternmost active volcano of

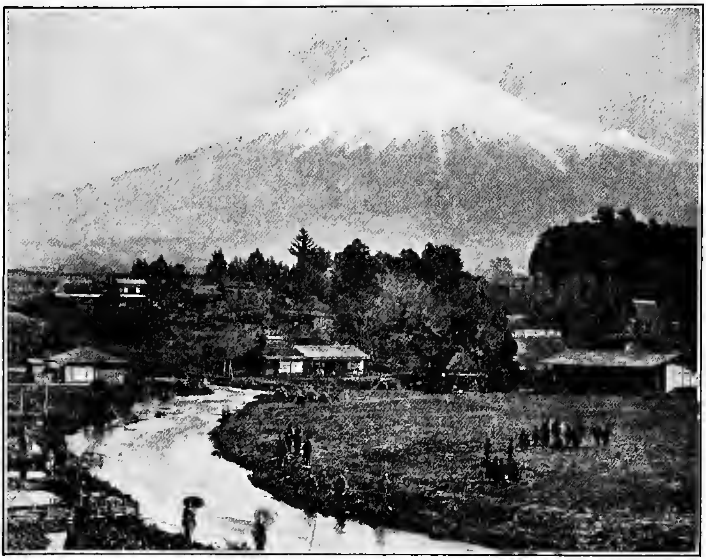


FIG. 310. — The symmetrical cone of Fujiyama in Japan.

this chain. Mount Edgecumbe at Sitka is probably only dormant, and lava flows near the Blue River in southeastern Alaska are surely postglacial. One is less than 50 years old, for there are charred and blackened tree trunks near its terminus.

Little is known about the volcanic history of the Alaskan volcanoes, though one, Bogoslof, in Bering Sea, has attracted special attention because of its unusual history. There had been here a volcanic rock rising from a shoal, but in 1796 a submarine eruption occurred and a new volcanic cone appeared, which in four years had grown to a height of several hundred feet above sea level. It stands in water 6000 feet deep, and Bogoslof is, therefore, only the top of a large volcano. The sea normally occupies its crater, and hence we have the explosions, by which its low, subaërial cones are periodically destroyed. Since 1796 there have been frequent eruptions and changes in the form and size of this new volcano, as the accompanying maps show (Fig. 311).

Katmai volcano (Fig. 295), on Alaska Peninsula, had a severe eruption in June, 1912. Complete darkness lasted for 60 hours at Kodiak, 100 miles distant. Dust fell at points 600 to 900 miles away, and fumes were reported at Vancouver Island, 1500 miles distant. The fall of from less than an inch to over 50 inches of ash near the volcano

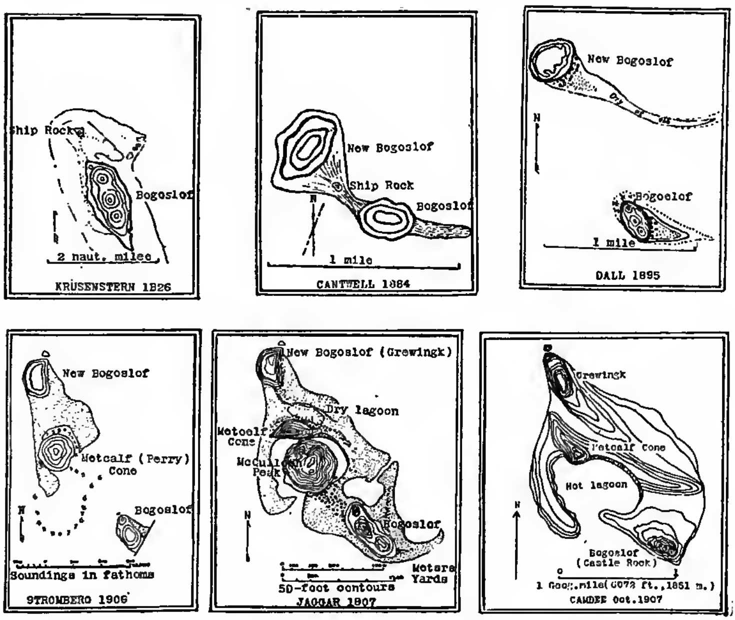


Fig. 311. — Maps of a few of the known stages in the recent history of Bogoslof, where a low cone is built up and then destroyed by an explosion. This has happened several times more since 1907. (After Jaggar.)

is shown in Fig. 312. The vegetation was buried, and natives were forced to move to new homes outside the afflicted district. Immense fields of pumice floated on the sea. The dust in the air was observed in distant parts of America and Europe, and may even have affected climate during the following year.

Volcanoes of Western United States

Former Activity. — So far as can be told, there are no active volcanoes in western United States. There is a partially authenticated record that Mount St. Helens was in eruption about 1841; and from

Mounts Baker, Rainier, and Hood sulphurous vapours and steam still rise. One of the fumeroles of the latter is said to have melted the glacier ice considerably in 1907. Carbon dioxide and other gases escape in association with many volcanoes of this region. Many of the cones are perfect in form, and the craters are not breached, proving that they have not long been inactive. There are also cinder cones of great freshness, and lava flows that cannot long have been exposed to the air. All these volcanoes, therefore, seem to be dormant. A short

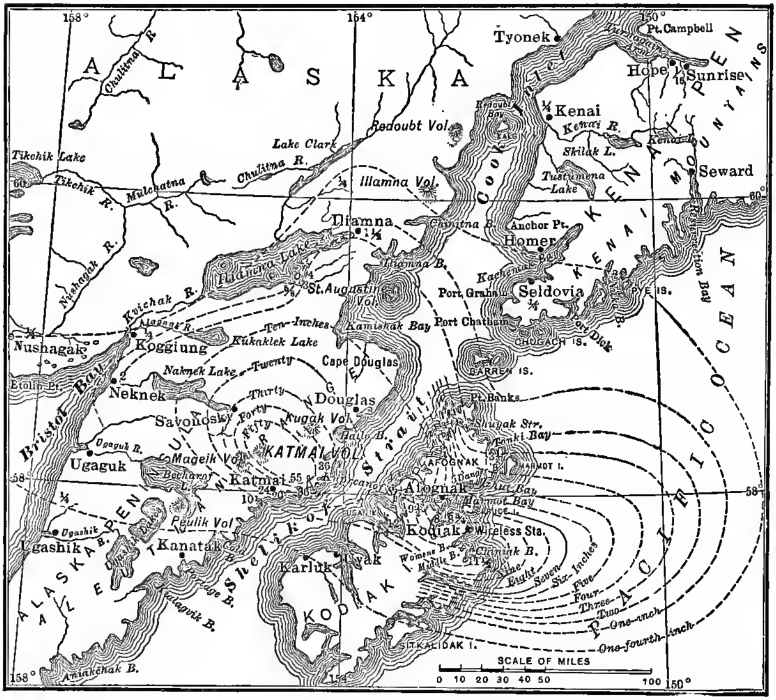


FIG. 312. — Map showing distribution of ash during the eruption of the volcano near Katmai, Alaska, in 1912. (G. C. Martin.)

distance north of Mount Baker, near Vancouver, B.C., there are volcanoes which are said to have been active since the Glacial Period.

In Arizona is Coon Butte, or Meteor Crater, thought by some observers to be an impact crater formed by a falling meteorite and by others to be related to explosion or subsidence in connection with deep-seated volcanic activity. Its walls are not igneous but sedimentary rock. On the other hand, borings in the centre have failed to reveal any meteorite (Fig. 313).

Volcanic activity in western United States has been present at various earlier periods, as is proved by abundant volcanic deposits and associated features. In the last period, which seems now to be nearly if not quite at an end, there was activity over a broad area, between the Rocky Mountains and the Pacific, and from Mexico to Canada. The activity was also prolonged, for there were great fissure eruptions, giving rise to lava floods; and lofty cones were built around some of the vents, such as San Francisco Mountain in Arizona, Mount Shasta in California, and Mounts Hood, St. Helens, Adams, Rainier, and

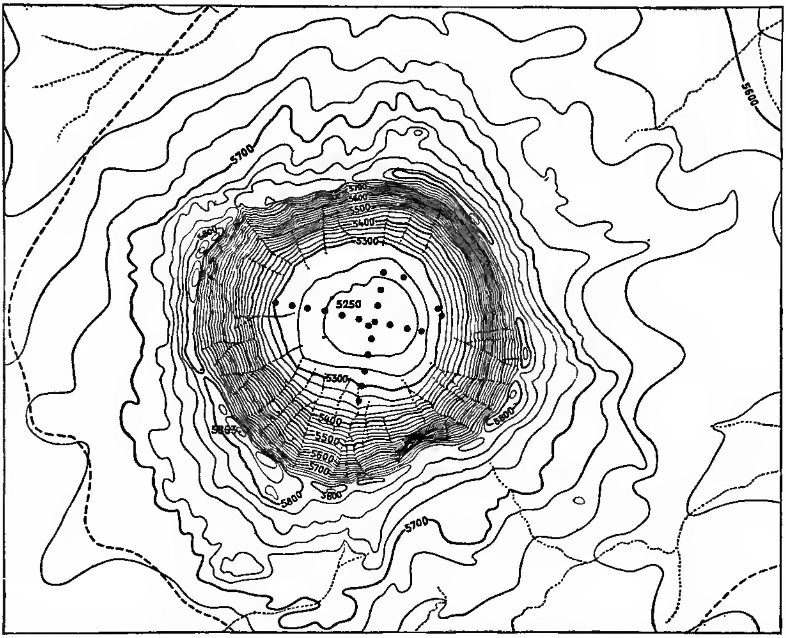


FIG. 313. — Topograpbic map of Coon Butte (scale 1 : 30,000), showing by black dots the positions of the holes drilled in the bottom of the crater in search for a meteorite. (Baker.)

Baker farther north. Some of them rival Etna in size and in grandeur — one is, for example, reminded of Etna by Shasta; and few mountains in the world have a grander symmetry than Mount Rainier as seen from Tacoma, or Mount Hood from Portland. Some of these cones may yet awake into activity, though upon this point prophecy is not safe (Figs. 157, 314).

Mount Shasta. — As an instance of a volcanic region in western United States we will take the case of Mount Shasta and vicinity. Shasta is a very symmetrical cone 14,380 feet high, seventeen miles in circumference at its base, having a volume of about 84 cubic miles.

It has been so long extinct that the summit crater is gone, but 2000 feet below the summit is a younger well-developed cone, known as Shastina, with a crater in its top. Definite lava flows are recognizable on the sides of the main cone, and there are numerous parasitic cones on the

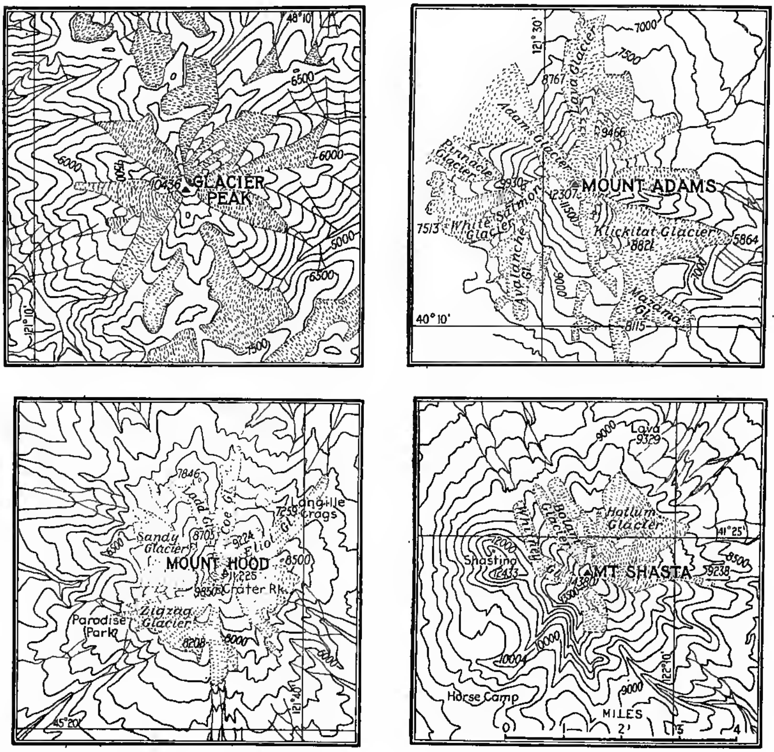


FIG. 314. — Topographic maps of four volcanoes of western United States. (After U. S. Geol. Survey.)

lower slopes and around the mountain base. It has apparently been extinct for many centuries.

Recent Eruption of Cinder Cone. — Eighty miles or more to the south of Shasta is Lassen Peak, one of a series of cones in a belt extending northwest and southeast. There are several large cones in this belt, Lassen Peak rising 10,437 feet, and there are large numbers of smaller cones. One of these, known as Cinder Cone, lies about ten miles from Lassen Peak. As the name indicates, it is made of volcanic ejecta, but a small lava flow extends out from its base. The cone rises 640 feet, is 2000 feet in diameter at the base, and has a perfect crater in its truncated top.

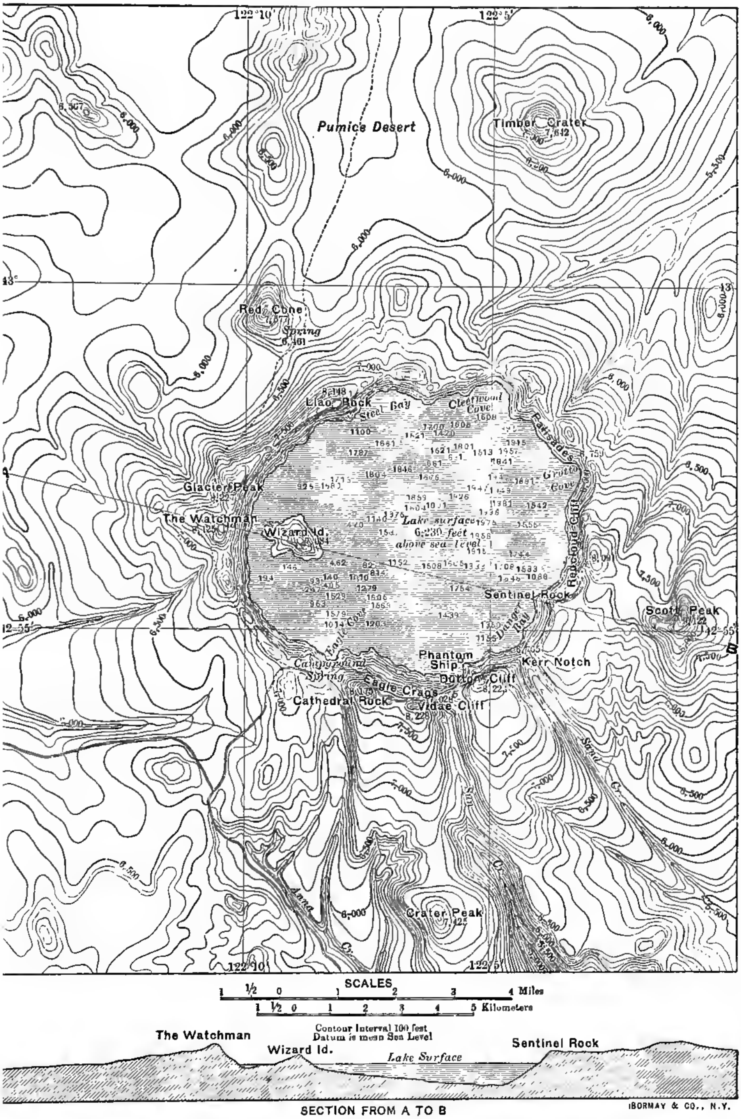


FIG. 315. — Map and cross-section of Crater Lake. (After U. S. Geol. Survey.)

It has been shown that there were at least two eruptions, separated by an interval of a century or more, the first being mainly ash, the second lava. The most interesting feature connected with these eruptions is the evidence of their recency; for trees killed by the ash still stand, and there are also standing trees in Snag Lake, which was formed by the lava dam, and by whose rise the trees were killed. It surely cannot have been a long time since these events happened, else the trees would have fallen. Apparently the last eruption occurred

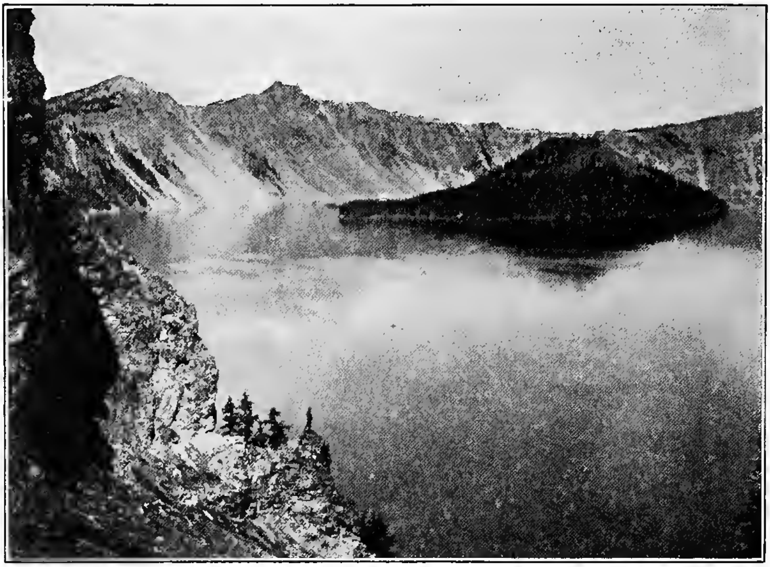


FIG. 316. — The inner walls of the caldera of Mt. Mazama, with Crater Lake and Wizard Island. (Russell, U. S. Geol. Survey.)

sometime in the first half of the last century, while the first eruption occurred a century or more earlier.

Since there are similar evidences of recent eruption in other parts of western United States, we may be certain that there has been volcanic activity there since the discovery of America, and probably even since the close of the War for Independence. That there should have been no great eruption since the settlement of the west by white men is certainly remarkable; but it does not prove that there may not yet be eruptions. Lassen Peak had a series of eruptions of moderate activity during the summer of 1914.

Crater Lake, Oregon. — This lake lies in a roughly circular crater, or caldera, five or six miles in diameter and about 4000 feet deep. The lake itself is 1996 feet deep and surrounded by nearly vertical walls from 900 to 2200 feet high. It is evidently in a truncated volcano, as are numerous other caldera lakes in the Eifel, in Italy, and in other regions. In this case the truncation is ascribed to subsidence, rather than explosion, it being believed that the volcano has been engulfed, perhaps because of the withdrawal of lava from beneath it (Fig. 315).

That a volcano, now called extinct Mount Mazama, once existed here is proved by the presence of valleys on the outer slopes, which extend up to the crater edge and are there truncated. Evidently there was once drainage from above, and the valleys have been beheaded. Another proof of the same conclusion is the presence of glacial scratches on the outer slopes, made by valley glaciers descending from some higher region, now gone. That is, there was evidently a mountain here, comparable to Mount Rainier, down which glaciers and streams flowed, and all the upper part of the mountain has disappeared.

The most natural explanation of such a phenomenon is that the top has been blown away by an explosion, as Vesuvius was in 79 and Krakatoa in 1883. But this is negatived by the absence of fragments round about. The conclusion is, therefore, forced that the mountain top has been lost by subsidence. Since this catastrophe a small cone has been built up in the lake, forming Wizard Island (Fig. 316). It is possible there are other calderas of the same origin.

Life History of a Volcanic Cone

The Young Volcanoes. — Many phases in the life history of a volcanic cone have been presented in the preceding statements with

Fig. 317. — Mt. Rainier, Washington, a young volcano. (A. H. Barnes.)

regard to individual volcanoes. It remains now to state these in résumé and carry the development further.

A volcano may start by explosion, great or small, pushing forth the fragments torn from the vent, together with ash or lava (Fig. 317). The site of the volcano may be on the sea floor or on the land; and the eruptive activity may cease with a single outburst, or it may continue for centuries. It is quite probable that other volcanoes may be built around open vents along a fissure from which lava floods at first poured, but which is no longer kept open except at one or more orifices.

Conflict of Forces. — As soon as the volcano is reared into the air, it begins to suffer from the attacks of subaërial denudation, and, if in the sea, from the attacks of oceanic agencies also. Thus all the time during its activity two opposing tendencies are at work, one tending

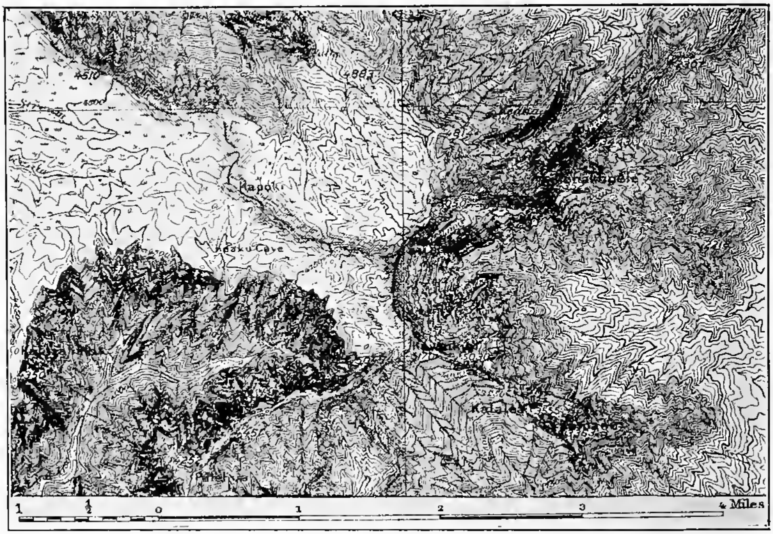
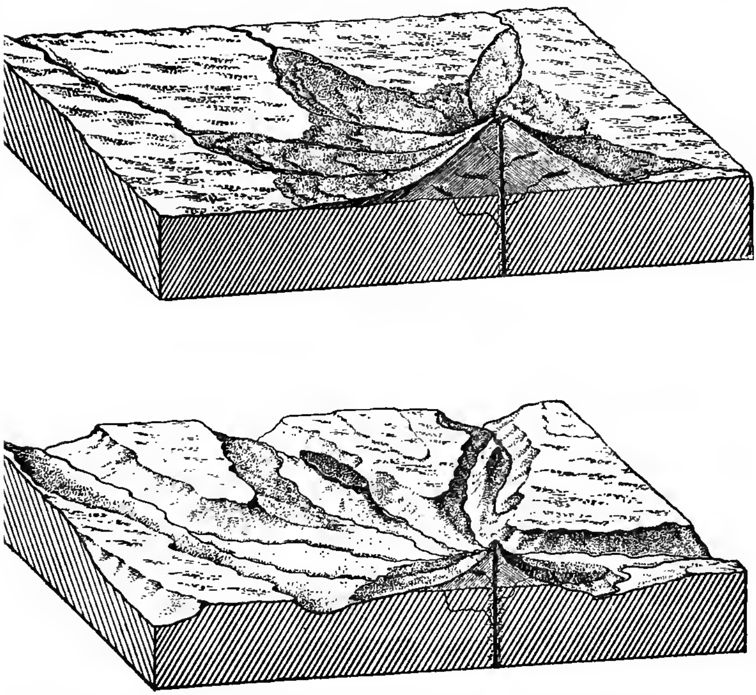


FIG. 318. — Canyons cut 2000 feet or more into the extinct cone of one of the westernmost of the Hawaiian Islands. (From map of Island of Kauai, U. S. Geol. Survey.)

to build it up, the other to remove it; but under normal conditions the work of upbuilding maintains mastery, while denudation serves merely to deface it and to render its growth less rapid. As the cone grows, its form will depend upon whether it is ash, or lava, or both combined, being flattest in the last case and steepest in the first. If activity continues, the sides are fissured and crossed by intruded dikes, while parasitic cones develop on the flanks and around the base. The period and phase of volcanic activity will vary, as we have seen in the preceding descriptions, and it may happen that the cone will be partly wrecked by violent explosion or by collapse. Each normal eruption will add to the cone, tending toward symmetry of form, and both ash and lava will serve in part to smooth over the irregularities caused by ıudation. But an explosion of abnormal violence, or a collapse, ıy completely destroy the symmetry.

Extinct Volcanoes Rapidly Denuded. — When eruptive activity ıses, the symmetrical cone will be gullied by radial streams (Fig. 318), ; crater, in which a circular lake may stand, will be slowly filled, and ; crater wall worn away and breached and finally destroyed, as in the ıe of the summit of Mount Shasta. As the cone is slowly worn away, ; dikes of resistant rock which traverse the weaker inclined beds of



. 319. — Block diagrams of a youthful volcano and its lava flows (upper), and an old dissected volcano (lower) with lava flows represented only by lava-capped mesas.

: cone may be etched into that wall-like relief from which the word *e* is derived. Waves also destroy volcanoes in the sea (Fig. 327).

)ld Volcanoes. — The central part of the cone will tend to remain highest (1) because there is more material, (2) because this is the .tre of the radial drainage, (3) because the rock here is most resist- . This is due to the fact that when lava solidifies below the sur- ɜ, it is more dense and less porous than when ejected into the air. ɜ vent therefore becomes filled with a solidified plug of resistant k, known as the *volcanic neck*, or *volcanic plug*, and this, because of its superior durability, will remain highest. In a region of extinct volcanoes, all stages in these processes of destruction may be seen, even the volcanic necks rising steeply above the surrounding surface, from which nearly, if not quite all, of the ejected material has been

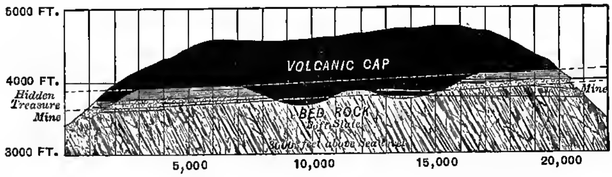


FIG. 320. — Volcanic cap on hilltop where ancient lava flow in a valley covered auriferous river gravels (circles). Subsequently erosion by streams on either side has converted the former valley bottom into a hilltop. (California State Mineralogist's Report.)

removed by denudation (Figs. 301, 319, 320). This is the last stage in the destruction of a volcano; and since the plug extends far down into the earth, it may remain a witness of eruptive activity of long-past ages. Such evidence is one of the proofs of ancient volcanic activity in Great Britain.

DISTRIBUTION OF VOLCANOES

The Two Volcanic Belts of To-day. — The great belt of active and recently active volcanoes is around the Pacific, and it has for that

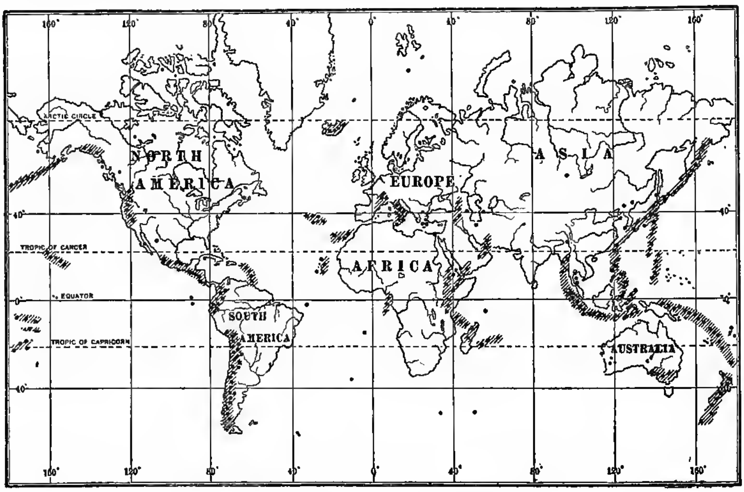


FIG. 321. — Distribution of active and recently extinct volcanoes.

reason been called "the ring of fire" (Fig. 321); this belt includes by far the greatest number of active cones. A second belt is traceable through the Mediterranean, western Asia, the East Indies, Central America, the Lesser Antilles, and the Azores. These two belts are in general the same as the two earthquake belts already mentioned (p. 417); they are also belts of present day and recent mountain growth. There are, however, many volcanoes outside these two belts, such as those of Mexico, Iceland, New Zealand, Mounts Erebus and Terror in the Antarctic, and a large number of oceanic volcanoes. In detail, groups of volcanoes are usually in linear belts, and along one or more lines, usually curved, as if on fissures.

Relationships of Location. — Most volcanoes are either in or near the sea, and a great number of them are on islands; indeed, most oceanic islands are either volcanoes or volcanic reefs. However, there are active volcanoes, and still more extinct ones hundreds of miles from the sea. The association of volcanoes with the ocean seems to be either (1) on swells or ridges rising from the sea floor, or (2) on or near the edge of the continent, where it slopes abruptly into the deep oceanic basins. In each case, and probably in all volcanoes, there is association with zones of crustal movement.

The Number of Volcanoes. — It is not possible to state, even approximately, the number of active volcanoes in the world, one difficulty being to determine which are active, for even a century or two of inactivity may not mean more than that the volcano is dormant. An estimate of 400 or 500 active volcanoes would probably not be too great, and the number may easily be twice that. Schneider states that 367 volcanoes are known to have been active in historical times. Recently extinct volcanoes are numbered by the thousands.

The Former Distribution of Volcanoes. — Many of the volcanic belts of to-day are along the line of, or close to, areas of former volcanic activity, proving that vulcanism can recur in the same region even after long intervals of quiet, as in the Auvergne region of central France and in the volcanic complex of the Yellowstone National Park. Other belts have apparently not had preceding volcanic activity. Again, belts in which there has been recurrent vulcanism have not witnessed present day or recent activity, as in the British Isles, and in northeastern United States. In both of these cases there has been profound volcanic activity in earlier ages, and the activity has come again and again; but for a long period there has been exemption from vulcanism. In northeastern United States, for instance, several geological periods have elapsed since the last phase of vulcanism in the Mesozoic age, a time period probably of millions of years.

Each age seems to have its own belts of volcanic activity, and while these often coincide with earlier or later belts, they may extend quite independently of any previous or subsequent vulcanism. The association in each case seems to be, as at present, with belts of crustal deformation, wherever these may lie. It is for this reason, too, that certain areas seem to have been exempt from volcanic activity throughout geological time. The plains of the Mississippi valley, for example, throughout most of their area have witnessed no vulcanism since the earliest geological ages. Their movements up and down have been unaccompanied by notable crustal deformation. Yet on the borders, as in central New York, dikes in places pierce the horizontal strata, though there is no reason for believing that the lava that was forced into them ever reached the surface. Lofty, broken plateaus, like the Colorado Plateau, share with mountains in volcanic outburst, but broad plains apparently do not, unless there is near-by crustal deformation.

Of these earlier eruptions there is little evidence left at the present day, excepting sheets of lava and ash, dikes, and volcanic necks or plugs. They are, therefore, of more interest to the geologist than to the physiographer. They influence the topography of to-day only as other strata of different origins might, if in similar position and with similar degree of resistance. They form no dominant topographic features, like volcanic cones, and they come in no direct, intimate relation to life as active volcanoes do.

Decline of Volcanic Activity

Mention has already been made of the former importance of lava eruptions from fissures, a phenomenon not now observed excepting in Iceland, and, on a small scale, on the flanks of active volcanoes. In the Tertiary time, however, lava issued from fissures in great volume, and spread over wide areas of country, as it had also done in earlier geological periods. There seem to have been periods of great volcanic activity, during which fissure eruptions occur, and these are followed by a period of declining vulcanism. The present appears to be such a period, following one of great activity; but whether in geological time there have ever been times of freedom from volcanic activity cannot be said. There is no proof that there ever were such periods, though it may also be said that there is no proof to the contrary.

During the decline in volcanic activity, fissure eruptions cease, volcanic vents remain open along fissures, and these, one by one, are closed. But even after a vent ceases to pour forth lava or ash, steam rises from the crater and from solfataras on and near the cone. This stage is followed by the escape of hot water and vapours of various kinds, and finally, before complete extinction, by warm springs, mineral springs, and carbon dioxide. Mount Hood has possibly reached the solfatara stage; the Yellowstone Park region and New Zealand is in the hot spring stage; and the Eifel is in the final stage when carbon dioxide alone issues.

Fissure Eruptions

Columbia Lava Plateau. — Although great fissure eruptions no longer occur, excepting possibly in Iceland, the effect of such eruptions in a recent geological period is stamped on the topography of parts of the earth, notably the Columbia and Snake River valleys in Washington and neighbouring parts of Idaho and Oregon (Fig. 322). Here, over an area of more than 200,000 square miles, the surface is underlaid by sheets of basaltic lava, one on the other, overlapping one another, and including between them soil beds and lake deposits, showing that sheet after sheet poured out with intervals between. Deposits of lapilli and other fragments prove that there was some explosive activity as well as the outflow of liquid lava, though such phenomena were exceptional. In places the lava flood of successive layers has covered the earlier surface of the land to a depth of over 4000 feet.

The lava flood rises on the bordering mountain sides, as the waters of a lake would; and they surround as islands (*steptoes*) the higher points which they did not completely overspread. Other peaks are completely buried by the horizontal layers of the encroaching lava flood. One peak 2500 feet high is buried by 1500 feet of lava. These lava floods have thus levelled up the surface and formed a broad lava plateau, not level but undulating, and crossed by deep canyons of rivers. These valleys are still in the stage of youth, and there are waterfalls and rapids, like the falls in the Spokane River at Spokane, and the Shoshone Falls of the Snake River in Idaho.

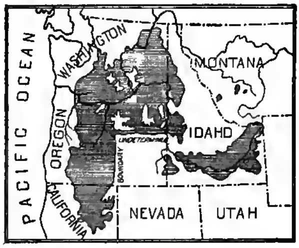


FIG. 322. — The lava plateau of the Columbia and Snake rivers.

In some places there are deep fissures, broadened to valleys or canyons and locally known as *coulées*. Portions of the plateau have been disturbed by orographic movements, and the western part of the lava-flooded area has been upturned to form a part of the Cascade Range. Most of the surface, however, is little disturbed by subsequent movement, and over large areas also there has been little denudation. The rolling surface apparently represents in large part the original undulations of the latest flows; and some of the swells and domes are cracked open, revealing the regular forms of the hexagonal basaltic columns. At a few points on the surface there are small cinder cones and low lava cones, but no large cones, and no visible surface indication of the source of the lava; but Russell discovered dikes in the canyons which might perhaps mark the sites of the fissures through which some of the overlying Columbia River lava rose. Some of it may have come from the low lava cones. As a result of Russell's latest work in the Snake River plains, he stated that no facts were known to prove fissure eruptions and that there, at least, he thought the lava came from numerous vents.

Other Lava Plateaus. — Similar, though smaller, lava floods occurred in northeastern Ireland and thence in disconnected areas along the west coast of Scotland, through the Hebrides and Faroe islands to Iceland, which is in the main a basalt plateau due to fissure eruptions, one of which, as already described, occurred in 1783. Similar larger basaltic lavas form plateaus in Abyssinia; and in India, the plateau of the Deccan, rivalling in area the Columbia Plateau, is also basaltic lava from fissure eruptions; but this lava is of an earlier age. It is also probable that fissure eruptions gave rise to some of the smaller lava plateaus of western United States, such as those of the Yellowstone Park.

Fertility of Lava Plateaus. — The broad, undulating basaltic plateau of the Columbia valley is covered with a deep, fertile residual soil of very fine grain, caused by the disintegration of the lava. In this rich soil lie the wheat fields for which central and western Washington and parts of Oregon are famous. Lava soils are often of notable fertility, and this fact is well illustrated in the Columbia Plateau.

Intruded Lavas

Igneous Rock Cooled below the Surface. — So far we have been concerned with the eruption of lava upon the surface of the earth; but there is another important phase of vulcanism, namely, that of intrusion of molten rock into the crust. Very probably such intrusions are in progress in parts of the earth to-day, and it is possible that some of the earthquakes are a result of the entrance of lava into the crust. Probably also some of the changes of level of the land are due to subterranean movements of molten rock. Minute changes of this sort in Japan have actually been measured.

When, in the course of long-continued denudation, a land surface is worn down to such intruded masses, they exert an influence upon the topography. Therefore, a knowledge of some of their characteristics is properly within the province of physiography. These intruded rocks occur in a variety of forms, among which the most important from the standpoint of physiography are volcanic necks, dikes, sheets or sills, laccolites, and batholites or bosses.

Volcanic Necks. — Being formed in the volcanic vent, as already stated, these forms of intrusion are roughly circular and of unknown depth. They consist of crystalline rock, often so resistant that they stand up above the surrounding surface as steep circular hills, sometimes being surrounded by sedimentary rocks through which the vent was drilled. There are numerous such volcanic necks in the Mount Taylor region of New Mexico. A form imitating the volcanic neck is a plug of lava thrust into the rocks, but not reaching the surface. The striking circular hill known as Mato Tepee in Wyoming has been interpreted in this way, but others think it is part of an eroded laccolite, and still others a denuded volcanic neck.

Dikes. — The origin of dikes through the solidification of lava in fissures in volcanoes and in connection with fissure eruptions has already been mentioned. Lava also rises toward the surface without reaching it, and in this way dikes are also formed. When a region of former volcanic activity has been worn down by denudation, it is often found to be crossed by multitudes of dikes, varying in width from a fraction of an inch to several yards. Sometimes the rocks are ramified by such dikes extending in all directions, and hundreds of them occurring in a single square mile. Some of these may have led to volcanic outbursts of long ago, all other signs of which have long since been worn away; others represent merely the ineffectual attempt of lava to rise to the surface. Such dikes are most common in regions of former volcanic activity; but they are sometimes present, as in central New York, where there is no reason to believe lava ever flowed out at the surface.

If dikes are more resistant than the rocks through which they cut, denudation etches them into relief. In some places they extend for hundreds of yards as steep-sided walls of rock, rising well above the surrounding region. If, on the other hand, the dike rock is weaker then the enclosing strata, it is worn away more rapidly and a valley or chasm is formed. Many chasms along the sea coast are worn out along such dikes.

In some cases rocks are crossed by so many dikes that a large proportion of their area is made up of these intrusions, and one can readily see that to find room for these intrusions, there must have been important lateral movement. When such an area is exposed to denudation, the intruded rock may be even more important in influencing the rate and resulting topographic form than is the country rock itself. It is said, however, that the Crazy Mountains of Montana and Mount Royal at Montreal owe their form primarily to the resistance of metamorphosed sediments, altered by contact with a central igneous stock and intruded dikes.

Sheets or Sills. — Lava, rising through fissures, may find a way in between the strata and there spread out in sheets between the layers, instead of rising and flowing out in surface lava sheets. These are known as intruded sheets or sills. They may be very thin, or they may have a thickness of scores of feet. It is sometimes difficult to tell the difference between an intruded sheet and a surface lava flow that has been covered by sedimentary layers. However, the surface of a sill is more compact, since the expansion of gases is less easy under the load of overlying strata than in a lava flow under only atmospheric pressure. Moreover, by its heat the intruded lava causes changes in the overlying rock such as a lava flow could not cause in rocks that were laid down after it had cooled. In many cases, too, the sill crosses from one layer to another, or small dikes extend from it into the overlying layers.

Sills are found in Great Britain, in western United States, in New Jersey and Connecticut, and in many other places. One of the best known instances is that of the Palisades of the Hudson; but there are others in the trap hills of New Jersey and the Connecticut valley. Being more resistant than the enclosing sandstones and shales, these intruded lavas have better withstood denudation, and, therefore, stand up as hills. Surface lava flows occur in this region also, and they produce similar topographic forms, one face being steep because the lavas are now tilted. Instances of topographic forms due to such lavas are Mount Holyoke and Mount Tom in Massachusetts, East and West Rocks at New Haven, Conn., and the trap hills near Orange, N.J.

In western United States lavas, both intruded sheets and surface flows, lie in horizontal position, and in the course of denudation they have resisted denudation. Therefore many buttes and mesas in this region owe their form to the influence of resistant lava.

Columnar Structure. — Both lava flows and sills often exhibit a remarkably perfect system of jointing, which, because best developed in the lava known as basalt, is often called basaltic jointing. Such jointing is also found in some volcanic rocks. Where most perfectly developed, the lava is crossed by a system of planes as a result of which the rock breaks away in the form of remarkably perfect hexagonal columns. This is true, for instance, at the Giant's Causeway in northern Ireland, so called because it is like a pavement or causeway (Fig. 323), at Fingal's Cave in western Scotland, and along the Rhine in Germany. In the latter place the columns have been quarried away for centuries, and great pits have been opened by their removal. The columns are so perfectly formed that, without further shaping, they can be used in building houses, in making dikes in Holland, for corner posts, etc. Less perfect jointing is seen in the Palisades of the Hudson, the word *palisade* being applied because of the columnar structure on the cliff face.

These joints are due to the strains set up by contraction of the lava during cooling, as a result of which the rock is broken. The hexagonal form due to contraction is also developed during the drying of a mud flat. It is a normal form resulting from equal contraction in a mass of a fair degree of homogeneity, for it is the most economical expenditure of the strains set up by the contraction. When a strain reaches the breaking point, it finds relief by breaking along three planes meeting at an angle of 120°, which is the angle of the hexagon. It is not to be assumed, however, that there is mathematical accuracy in the result, for variations are introduced due to difference in the rate of cooling, in the composition of the rock, and doubtless in other ways. While the majority of the columns are more or less perfectly hexagonal, there are columns with more than six sides and others with five, four, and three sides.

The hexagonal columns usually develop at right angles to the cooling surface, and, therefore, extend from the surface toward the base of the sheet. The individual columns are commonly broken across by gently curved planes, forming a ball-and-socket joint. These are due to contraction and breaking in the columns themselves. The prisms vary in diameter from an inch or two up to a foot and a half or more, and they are sometimes over a hundred feet long. When most perfectly developed they are so regular as to seem

FIG. 323. — Basaltic columns at Giant's Causeway in Ireland.

almost artificial. Because of the remarkable appearance of the basaltic columns many people visit Fingal's Cave and the Giant's Causeway.

Laccolites. — Gilbert has called attention to the fact that in the Henry Mountains of Utah such large quantities of lava were intruded between the layers that the overlying rocks were pushed up in a large dome. The lava rising toward the surface found it easier to lift the overlying rocks than to break through them, and there resulted an intrusion of large quantities of lava instead of volcanic outflow (Fig. 324). Thus, instead of building an ash cone or a lava volcano on the surface, a great reservoir of lava was thrust into the strata. Such an intruded mass is a *laccolite*, and the dome mountain which is raised above the intrusion is a laccolitic mountain. Denudation has stripped off much of the overlying cover of stratified rocks in the Henry Mountains, and revealed the lava core, now long since cooled and solidified (Fig. 343). Other cases of laccolites are now known.

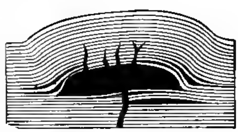


FIG. 324. — Cross-section of a laccolite. (Gilbert.)

Batholites or Bosses. — In many cases the wearing down of mountains has revealed an underlying basement of granitic rock, often many miles in extent, which has risen beneath the mountains, has broken through or melted away the strata, and has solidified in complex relation to the overlying strata. Such great intruded masses are *bosses* or *batholites* or *batholiths* (Figs. 22, 325). It is probable that similar intrusions are at present in progress beneath rising mountain masses; and they may be the reservoirs from which the volcanoes are being supplied. Certainly in the past batholitic intrusion has been a common phenomenon of mountain uplift.

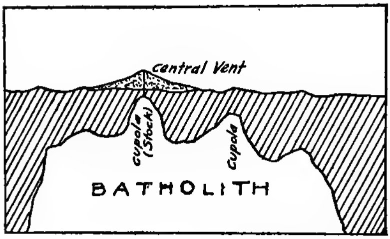


FIG. 325. — Diagram to show relationships of lava cooling underground in large masses. (Daly.)

When by denudation the overlying strata are removed, and the batholitic basement rocks revealed, there is a difference in topographic form, as is shown in the chapter on mountains (p. 528). The massive, crystalline, igneous rocks are very different in character from the stratified rocks beneath which the batholites lie. Old mountains, long exposed to denudation, are often mainly made up of granites and other coarsely crystalline igneous rocks which were raised to their present position as batholitic intrusions.

IMITATIVE FORMS

Geysers, already described, closely imitate volcanoes in important respects. They always have a crater; there is often a cone around the crater; and there is intermittent eruption. In geysers, however, only steam, hot water, and dissolved substances are commonly extruded; and the cone is made of deposits from solution, not of ash or lava.

Mud volcanoes are formed where steam or other gases rise through mud deposits, throwing out the mud, which builds a cone around the vent. Small cones of this sort are found in the paint pot areas of the Yellowstone Park. Others are formed in Iceland, Sicily, and other regions of present or recent volcanic activity. They may erupt continuously or intermittently, and, in some places, cones a hundred feet or more in height are built.

Some of the mud volcanoes, also called mud-lumps and mud cones, are due to the development of gases underground by some form of decomposition or slow combustion. Mud volcanoes in Sicily have been explained as a result of the slow combustion of sulphur; others are explained by the decay of vegetation, and to other forms of chemical change underground. In the lower Indus there are great numbers of mud cones over an area of 1000 square miles, some of them rising 300 or 400 feet and with craters 30 yards across. Mud-lumps, from which gases and salt water issue, also occur at the mouth of the Mississippi (p. 158); but these are evidently related to the river rather than to the gases. A dome or gas volcano 30 or 40 feet high and 3 acres in extent was formed in the Caribbean Sea near Trinidad in November, 1911. It seems clear that it was pushed up by gas, which subsequently ignited.

Fig. 326. — Craters on the moon, usually interpreted as of volcanic origin. (Nasmyth and Carpenter.)

Subterranean fires may also cause imitation of volcanic phenomena. An instance of this was seen in 1898 by the author in the Bad Lands of North Dakota, near Medora, where a coal seam had taken fire. Gases issued from cracks and orifices in the ground and there were a few small cones, while fragments of slaggy rock, baked and partly melted, were strewn about, causing a close imitation of volcanic phenomena on a small scale.

Influence of Vulcanism on Man

Destructive Influences. — The pages of this chapter have recorded numerous instances of the destructive work of volcanoes, and this is by far the most striking phase of the influence of vulcanism on man. Illustrations, similar in kind, could be greatly multiplied, showing the destruction of life and property by volcanic eruption. Doubtless hundreds of thousands of lives have been lost by this cause, and in the sea millions of fish are killed by volcanic eruptions.

Production of Fertile Soil. — There are, however, other influences of importance which may be reckoned as beneficial. One of these is the influence upon soil. Many lavas give rise upon their disintegration to extremely fertile soils. This is illustrated in the neighbourhood of Vesuvius, where the dense agricultural population along the shores of the Bay of Naples are, over much of the area, tilling fertile volcanic soils. The soils of the great lava plateau of Washington and Oregon furnish another instance, and there are many others.

Formation of Ore Deposits. — Vulcanism has also played an important rôle in the development of many mineral veins. Their heat and the gases which they bring have given to water a solvent power of great potency in the transfer of mineral from one point to another; and the lavas have contributed much of the mineral for solution, transportation, and deposition in veins. A large part of the mineral wealth of the world is accessible to man because of changes in which vulcanism has played an important part, either directly or indirectly. Even mineral deposits are in some cases now thought to be of eruptive origin, as in the case of the enormous iron deposits at Kiruna in Sweden.

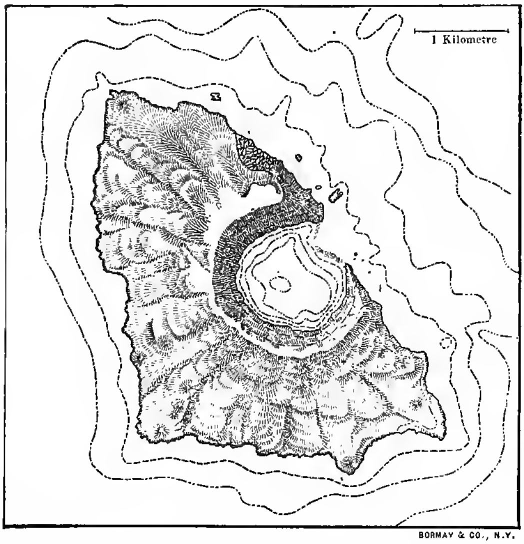


FIG. 327. — Crater harbour of the island of St. Paul, an extinct volcano breached by the waves.

Other Influences. — Vulcanism has introduced rock conditions which have greatly influenced topographic form, both directly by deposit and indirectly by influencing denudation. It has formed lakes, diverted and directed stream courses, and given rise to conditions in underground circulation, as a result of which mineral and medicinal waters of value have been caused. It is probable also that the movements of molten rock beneath the surface are responsible for some earthquakes, even some of the greatest, and for changes in the level of the land, perhaps even for some of the major topographic features of the earth.

Vast Importance of Vulcanism. — By transferring rock within the earth to the surface, vulcanism is responsible for vast and complex results through the denudation of the geological ages. It is likewise probable that the addition of water vapour, carbon dioxide, and other gases is a matter of the highest importance in maintaining that balance of conditions upon which life depends; and it is not at all improbable that this balance has been subject to important variations with differences in the extent of volcanic activity. This, however, is not a point upon which it is as yet possible to speak with definiteness. One can hardly be mistaken in assigning to vulcanism a high place in the economy and activities of the earth on which we dwell, — a far higher importance than merely that of volcanic outbursts, the building of volcanic cones, and the destruction of life and property. These are but minor expressions of one of the great phases in earth activity, basal in importance in terrestrial development, and perhaps even to life on the planet.

The Cause of Volcanic Action

Molten Rock and its Extrusion. — The question of the cause of volcanic action resolves itself into two parts: (1) the cause of the molten rock, (2) the reason why this rock rises into the crust and to the surface of the earth. The consideration of the cause of the molten rock may for the present be deferred, since it involves the general question of the condition of the earth's interior; and how this condition affects not only vulcanism, but changes of level of the land, earthquakes, mountain formation, and even the formation of continents and ocean basins.

Existence of Molten Rock, or Magma. — In order to explain vulcanism alone, we may start with the undoubted fact that there is below the surface, either locally or generally, a supply of heated rock, which, under favourable conditions, can be forced into the crust and to the surface in liquid form. It is not to be assumed that this heated rock is necessarily in the liquid form where it lies; it may be hot enough to melt under atmospheric pressure but prevented from expanding to the liquid form by the pressure of the overlying rocks, and changed to the liquid state only when that pressure is sufficiently relieved.

Objections to a General Magma. — It is sometimes stated that the magma from which the lava is derived cannot be generally distributed beneath the crust because (1) vulcanism is present only in limited parts of the earth; (2) neighbouring volcanoes may erupt quite different lavas; (3) neighbouring volcanoes sometimes show no sympathetic relation — notably Mauna Loa and Kilauea. These objections are, however, not necessarily fatal to the theory of a general magma. The areas where volcanoes occur may be lines along which pressure is relieved; one volcano may very well send forth different lava from a neighbour if its supply comes from a different level in the magma, or from a magma that has been locally differentiated; and of two volcanoes side by side, but unsympathetic, one may have its supply from a local reservoir disconnected from the main magma.

Facts Indicating a General Magma. — Far more important than the three evidences opposed to a general magma is the evidence of quite the opposite condition. Facts have accumulated to indicate that there is a sympathetic response even between distant volcanoes, and between volcanic eruption and earthquakes. It can scarcely be an accident that Pelé and Soufrière, 90 miles apart, were in eruption at the same time; that the Icelandic eruption of 1783 was preceded by a volcanic outburst many miles away; that, when Vesuvius is active, eruptions occur in other vents of the adjacent volcanic field, to mention only three of the many cases of apparent sympathy between volcanoes. This is a subject upon which it is important to gather more facts, but such facts as are known seem to point to the existence of widespread magma, locally tapped by fissures or volcanic vents.

Relation of Deformation to Extrusion. — The parts of the magma which are tapped appeared to be mainly, if not entirely, in regions of crustal deformation at the present time; and in earlier geographical ages to have been zones of crustal deformation of that day. There are three possible ways in which such deformation may induce the rise of molten rock from the magma: (1) by relieving the pressure locally along lines of upfolding and thus permitting the change to the fluid state, (2) by forming fissures and otherwise weakening the crust so that the molten rock can rise, (3) by the squeezing up of the lava under mountain arches by the downsinking of neighbouring areas. All three of these influences may be at work in producing vulcanism.

Already evidence has been presented in support of the conclusion that fissure lines are sought as pathways of escape for the molten rock; but it must be stated that the rising lava itself may be largely responsible for the opening of the fissures. This surely must be the case at such depths in the earth as lie in the zone of flowage, where open cracks cannot exist. That the magma rises under mountain arches either by the release of pressure, or by being forced upward by downward pressure near by, is already indicated by the great batholitic masses which denudation has revealed in the cores of mountains. It is highly probable that these batholites were themselves (1) magma that rose up under and into the rising mountains, and (2) the source of volcanic supply for ash and lava eruptions that built volcanic cones upon the mountains, as similar cones are now building in various parts of the earth.

Relation of Gravity and Included Gases to Extrusion. — The rise of the molten lava into the crust and to its surface is evidently due to the influence of (1) gravity, (2) included gases. Such a phenomenon as the slow ascent of lava in the conduit of Mauna Loa until the pressure becomes great enough to give escape to the lava through the side of the cone, and then a recurrence of the ascent of the lava has the appearance of hydrostatic adjustment. The ascent of batholitic masses beneath mountains seems likewise to be the result of gravitative adjustment of a fluid to pressure. The great outflows of basalt from fissure eruptions seem explicable only on the theory that they were squeezed out by a pressure on the molten rock, and that their rise was, therefore, essentially a result of gravity. It is highly probable that the greater amount of the rising of lava into the crust is similarly a result of gravitative adjustment.

But, even granting this, there remain phenomena of vulcanism which can be explained only on the basis of the expansive force of the included gases. These phenomena may all be essentially surface phenomena, expressed only when the liquid rock reaches the upper portions of the crust and, therefore, attains points where the pressure is so reduced that the expansive force of the gases may express itself and expel some of the lava. Certainly the final stage in many volcanic eruptions is primarily the result of explosive action of expanding and probably combining gases.

Origin of Gases in Lavas. — There has been speculation as to the origin of the included gases. It has been proposed, for example, that the water vapour is the result of entrance of sea water into the magma, but this seems impossible, first because the sea bottom deposits are so compact that percolation must be very slow; and, secondly, because the earth itself is impervious at depths well above the level of the magma in the zone of rock flowage, which lies at depths no greater than about 12 miles. Some surface water doubtless finds its way to volcanic vents, and possibly to reservoirs of lava in the upper crust; but that such vast quantities as are emitted from volcanoes could thus find their way to the molten rock is too utterly incredible for belief. The amount that thus enters the lava may have an effect in aiding in the final eruption. It has been observed that the eruptions of Kilauea most frequently occur in the rainy season; and that Etna and Vesuvius have most often erupted in winter and spring, the times when there is most rain. These observations are not sufficient to establish the conclusion, but they at least suggest the possibility that when an eruption is almost ready to occur, the entrance of surface waters may give the last impulse necessary for the outbreak.

The included gases as a whole, however, seem quite certainly to be a component part of the original magma. They may well be a part of the original earth material which was never before at the earth's surface until expelled during an eruption. If this view is correct, the aid of volcanoes in supplying water vapour, carbon dioxide, and other gases to the air is a matter of very considerable importance; for not only are huge volumes poured forth during each eruption, but, for centuries after volcanic activity ceases, these gases continue to issue from the volcanic centres. Even the composition of the atmosphere and the volume of the ocean waters may be affected.

Suggestion of Isolated Subterranean Reservoirs. — On the theory of volcanic action as stated above, it is quite possible for some of the molten rock to rise into the crust, forming reservoirs more or less disconnected from the interior magma, and much nearer the surface. Such a condition would account for failure of neighbouring volcanoes to erupt sympathetically in some cases, and it might also account in part for differences in composition of lavas. If there are such reservoirs, perhaps batholitic in character, surface waters may descend to them, and, in these cases, become a more important factor in the extrusion of the lava than is assumed above. Reservoirs of this character would gradually fail to supply lava for extrusion, and volcanic activity would finally die out. These possibilities are not suggested as alternate hypotheses for the theory of volcanic activity stated above, but as possible variations of conditions under that theory.

Cessation of Crustal Movements and of Vulcanism. — On the theory here proposed the gradual dying out of volcanic activity in a region is assigned to the diminution of those crustal movements as a result of which the interior magma is forced upward into the crust; but locally eruption may continue by the accession of underground waters even after the crustal movements ceased. If this interpretation is correct, the present is a time of relatively slight crustal deformation, as it seems to be one of waning volcanic activity.

Other Hypotheses of Vulcanism. — The explanation of volcanic phenomenon here presented is not to be considered a demonstrated conclusion. It is an hypothesis framed upon the basis of the known data, and it has the merit of satisfactorily accounting for most of the facts. There are, however, some difficulties and it does not by any means meet with universal acceptance, though to the writer it appeals as the best founded of the various hypotheses put forward to explain volcanic phenomena. There are numerous such hypotheses, but this is not the place for their discussion. It will suffice to state one or two of the leading lines of difference between them and the hypothesis here presented.

There are some who assign to percolating waters a far higher value in volcanic eruption than is here given, and some students of the subject are inclined to assign to downward percolation of water a dominant part in the expulsion of lava from within the earth. As stated above, also, there are students of vulcanism who are not ready to admit the existence of a widespread and practically universal magma, but who consider vulcanism to be a localized phenomenon because of localized cause for heat. Three causes for the development of local areas of sufficient heat to melt rocks have been proposed: (1) the influence of radium, (2) chemical changes, (3) heat developed by pressure and by movement during crustal deformation. That each of these is a source of heat is an undoubted fact; but that either is competent to account for the melting of the rocks on the vast scale required by present and past vulcanism is by no means demonstrated.

Perhaps the strongest reason for doubting the existence of a general magma of heated rock, which on relief of pressure may flow as a liquid and rise into the crust and even to the surface, is the fact that vulcanism of the remote geological ages has apparently been no more active than in the present and recent past. Indeed, it is very doubtful whether at any geological period there has been greater volcanic activity than in the Tertiary period which immediately preceded the present. If vulcanism is due to the presence of a general heated magma which has been in existence during the earth's history, igneous activity would be expected to show a gradual diminution during the geological ages as the cold crust thickened by loss of heat. In order to account for the continuation of vulcanism, it would seem that there must be some cause for replenishing the past loss by radiation into space. This argument leads some to seriously doubt the existence of a general magma and looks to local causes for the generation of the heat which expresses itself in vulcanism.

Further consideration of the problems presented by phenomena due to interior conditions is undertaken in a subsequent chapter.

References to Literature

R. Anderson. The Great Japanese Volcano Aso, Pop. Sci. Monthly, Vol. 71, 1907, pp. 29–49; *ibid.*, Journ. Geol., Vol. 16, 1908, pp. 499–526.

T. Anderson. On Certain Recent Changes in the Crater of Stromboli, Geog. Journ., Vol. 25, 1905, pp. 123–238; The Volcano of Matavanu in Savaii, Quart. Journ. Geol. Soc., Vol. 66, 1910, pp. 621–639.

J. M. Arreola. The Recent Eruption of Colima, Journ. Geol., Vol. 11, 1903, pp. 749–761.

S. Arrhenius. Lehrbuch der Kosmischen Physik, Leipzig, 1903, pp. 278–347; Geol. Fören i Stockholm Förhandl., Vol. 22, 1900, pp. 395–419.

D. M. Barringer. Coon Mountain and Its Crater, Proc. Acad. Nat. Sci. Phila., Vol. 57, 1905, pp. 861–886; Meteor Crater in North Central Arizona, 1910, 24 pp.

J. M. Bell. The Great Taraivera Volcanic Rift, New Zealand, Geog. Journ., Vol. 27, 1906, pp. 369–382.

T. G. Bonney. Volcanoes, New York, 1899, 332 pp.

A. Brun. Recherches sur l'Exhalason Volcanique, Geneva, 1911.

T. C. Chamberlin and R. D. Salisbury. Geologic Processes, New York, 1905, pp. 590–637; *ibid.*, Vol. 2, 1906, pp. 99–106.

W. Cross. The Laccolitic Mountains of Colorado, Utah, and Arizona, 14th Ann. Rept., U. S. Geol. Survey, Part 2, 1894, pp. 157–241; Table Mountains, Monograph 27, U. S. Geol. Survey, 1896, pp. 285–316.

R. A. Daly. The Nature of Volcanic Action, Proc. Amer. Acad. Arts & Sciences, Vol. 47, 1911, pp. 47–122; Mechanics of Igneous Intrusion, Amer. Journ. Sci., 4th series, Vol. 15, 1903, pp. 269–298; *ibid.*, Vol. 16, 1903, pp. 107–126; *ibid.*, Vol. 26, 1908, pp. 17–50; Abyssal Igneous Injection as a Causal Condition and as an Effect of Mountain Building, *ibid.*, Vol. 22, 1906, pp. 195–216; Igneous Rocks and their Origin, New York, 1914, 563 pp.

J. D. Dana. Characteristics of Volcanoes, New York, 1890, 399 pp.

W. M. Davis. The Triassic Formation of Connecticut, 18th Ann. Rept., U. S. Geol. Survey, Part 2, 1898, 192 pp.; Vulkanische Formen, Erklärende Beschreibung der Landformen, Leipzig, 1912, pp. 316–351.

A. L. Day and E. S. Shepherd. Water and Volcanic Activity, Bull. Geol. Soc. Amer., Vol. 24, 1913, pp. 573–606.

J. S. Diller. Latest Volcanic Eruptions of the Pacific Coast, Science, N. S., Vol. 9, 1899, pp. 639–640; Mt. Shasta, National Geographic Monographs, New York, 1896, pp. 237–268; A Late Volcanic Eruption in Northern California, Bull. 79, U. S. Geol. Survey, 1891, 33 pp.; Crater Lake, Prof. Paper 3, U. S. Geol. Survey, 1902, 167 pp.

C. E. Dutton. Hawaiian Volcanoes, 4th Ann. Rept., U. S. Geol. Survey, 1884, pp. 75–219; Mt. Taylor and the Zuñi Plateau, *ibid.*, 6th Ann. Rept. 1885, pp. 105–198; Volcanoes and Radioactivity, Journ. Geol., Vol. 14, 1906, pp. 259–268.

C. R. Eastman. Vesuvius during the Early Middle Ages, Pop. Sci. Monthly, Vol. 69, 1906, pp. 538–566.

F. Fouqué. Santorin et Ses Eruptions, Paris, 1879, 440 pp.

I. Friedlander. Karten des Eruptionskegels des Vesuv und des Vesuvkraters, Petermanns Geog. Mitteilungen, Vol. 58, 1912, Tafeln 43, 44.

A. Geikie. Among the Volcanoes of Central France, Geological Sketches, New York, 1892, pp. 74–108; The Lava Fields of Northwestern Europe, *ibid.*, pp. 239–249; Ancient Volcanoes of Great Britain, New York, 1897.

J. Geikie. Old Scottish Volcanoes, Scottish Geog. Mag., Vol. 23, 1907, pp. 449–463.

G. K. Gilbert. Report on the Geology of the Henry Mountains, U. S. Geog. and Geol. Survey of the Rocky Mountain Region, Washington, 1880, 170 pp.; Laccolites in Southeastern Colorado, Journ. Geol., Vol. 4, 1896, pp. 816–825.

W. Lothian Green. Vestiges of a Molten Globe, Part 1, London, 1875, 59 pp.; Part 2, Honolulu, 1887, 337 pp.

A. Harker. The Natural History of Igneous Rocks, New York, 1909.

A. Heilprin. The Tower of Pelée, Philadelphia, 1904, 62 pp.; Mt. Pelée and the Tragedy of Martinique, Philadelphia, 1903.

C. H. Hitchcock. Hawaii and Its Volcanoes, Honolulu, 1909, 314 pp.

W. H. Hobbs. The Grand Eruption of Vesuvius in 1906, Journ. Geol., Vol. 14, 1906, pp. 636–655; Some Considerations Concerning the Place and Origin of Lava Maculæ, Beiträge zur Geophysik, Vol. 12, 1913, pp. 329–361.

R. S. Holway. Recent Volcanic Activity of Lassen Peak, Univ. California Publications in Geography, Vol. 1, 1914, pp. 307–330.

E. O. Hovey. Observations on the Eruptions of 1902 of La Soufrière, St. Vincent, and Mt. Pelée, Amer. Journ. Sci., 4th series, Vol. 14, 1902, pp. 319–358; Bull. Amer. Museum Nat. Hist., Vol. 16, 1902, pp. 333–372; The New Cone of Mt. Pelée and the Gorge of the Rivière Blanche, Amer. Journ. Sci., Vol. 16, 1903, pp. 269–281; Ten Days in Camp on Mt. Pelée, Martinique, Bull. Amer. Geog. Soc., Vol. 40, 1908, pp. 662–679; Camping on the Soufrière of St. Vincent, *ibid.*, Vol. 41, 1909, pp. 72–83; The Grande Soufrière of Guadeloupe, *ibid.*, Vol. 36, 1904, pp. 513–530.

E. Hull. Volcanoes: Past and Present, London, 1892, 266 pp.

T. S. Hunt. Chemical and Geological Essays, Boston, 1875, 489 pp.

J. P. Iddings. Origin of Igneous Rocks, Bull. Phil. Soc. Washington, Vol. 12, 1892, pp. 89–124; Bysmaliths, Journ. Geol., Vol. 6, 1898, pp. 704–710; Yellowstone Park, Monograph 32, U. S. Geol. Survey, Part 2, 1899, pp. 1–164, 215–440; Igneous Rocks, New York, Vol. 1, 1909, pp. 296–333; *ibid.*, Vol. 2, 1913, pp. 343–657.

T. A. Jaggar, Jr. The Evolution of Bogoslof Volcano, Bull. Amer. Geog. Soc., Vol. 40, 1908, pp. 385–400; Weekly Bulletin of Hawaiian Volcano Observatory, Vol. 1, 1913, to date.

T. A. Jaggar, Jr., and E. Howe. The Laccoliths of the Black Hills, 21st Ann. Rept., U. S. Geol. Survey, Part 3, 1901, pp. 163–303.

D. W. Johnson. Volcanic Necks of the Mount Taylor Region, New Mexico, Bull. Geol. Soc. Amer., Vol. 18, 1907, pp. 303–324; A Recent Volcano in the San Francisco Mountain Region, Arizona, Bull. Geog. Soc. Phila., Vol. 5, 1907, pp. 6–11.

H. J. Johnston-Lavis. The South Italian Volcanoes, Naples, 1891, 342 pp.; The Eruption of Vesuvius of April, 1906, Trans. Roy. Soc. Dublin, series II, Vol. 9, 1908.

J. W. Judd. Volcanoes, New York, 1881, 381 pp.

A. Lacroix. La Móntagne Pelée et ses Éruptions, Paris, 1904; La Móntagne Pelée après ses Eruptions, Paris, 1908.

G. D. Louderback. The Relation of Radioactivity to Vulcanism, Journ. Geol., Vol. 14, 1906, pp. 747–757.
Sir Charles Lyell. Graham Island, Principles of Geology, 11th edition, Vol. 2, 1873, pp. 58–63; Skaptár Jokul in Iceland, *ibid.*, Vol. 2, pp. 48–53; Monte Nuovo, *ibid.*, Vol. 1, pp. 606–616.
E. de Margerie. Deux Accidents Cratériformes, Annales de Géographie, Vol. 22, 1913, pp. 172–184.
G. C. Martin. The Recent Eruption of Katmai Volcano in Alaska, Nat. Geog. Mag., Vol. 24, 1913, pp. 131–181.
W. C. Mendenhall. The Wrangell Mountains, Alaska, Nat. Geog. Mag., Vol. 14, 1903, pp. 395–407.
G. Mercalli. I Vulcani Attivi della Terra, Milan, Vol. I, 1907, 421 pp.
G. P. Merrill. The Meteor Crater of Canyon Diablo, Smithsonian Misc. Collections, Vol. 50, 1908, pp. 461–498.
E. Ordóñez. Le Jorullo, Guide Book 11, Tenth International Geological Congress, 1906, 55 pp.
R. D. Oldham. Lava Plateau of the Deccan, Medlicott and Blandford's Manual of the Geology of India, Calcutta, 1893, pp. 255–284.
F. Omori. The Usu-san Eruption and the Earthquake and Elevation Phenomena, Bull. 5, Imperial Earthquake Investigation Committee, 1911, pp. 1–37; *ibid.*, 1913, pp. 101–107.
F. A. Perrett. Vesuvius: Characteristics and Phenomena of the Present Repose Period, Amer. Journ. Sci., Vol. 178, 1909, pp. 413–430.
J. Phillips. Vesuvius, Oxford, 1859.
Gaius Pliny. Pliny's Letters, Book 6, translation from the Latin in Shaler's Aspects of the Earth, pp. 50–56.
W. E. Pratt. The Eruption of Taal Volcano, Philippine Journal of Science, Vol. 6, 1911, pp. 63–83.
F. L. Ransome. Some Lava Flows of the Western Slope of the Sierra Nevada, Cal., Bull. 89, U. S. Geol. Survey, 1898, 74 pp.
H. H. Robinson. The San Franciscan Volcanic Field, Arizona, Prof. Paper 76, U. S. Geol. Survey, 1913, 213 pp.
I. C. Russell. Volcanoes of North America, New York, 1897, 346 pp.; Lava Plateau of Columbia and Snake Rivers, U. S. Geol. Survey, Bull. 108, 1893; Water Supply Paper 4, 1897; 20th Ann. Rept., Part 2, 1900, pp. 129–134; Water Supply Papers 53, 54, 1901; Bull. 199, 1902, pp. 59–134; Bull. 217, 1903; Water Supply Paper 78, 1903; Bull. 252, 1905; Igneous Intrusions in the Neighborhood of the Black Hills, Journ. Geol., Vol. 4, 1896, pp. 23–43.
K. Sapper. Die Mittelamerikanischen Vulkane, Petermanns Mitteilungen, Ergänsungsheft 178, 1913, 173 pp.
D. Sato. Eruption of Mt. Usu, Bull. 23, Survey of Japan, 1913, pp. 1–13.
K. Schneider. Die Vulkanischen Erscheinungen der Erde, Berlin, 1911, 272 pp.; Zur Geschichte und Theorie des Vulkanismus, Prague, 1908, 113 pp.
P. Scrope. Geology of the Extinct Volcanoes of Central France, London, 1858, 258 pp.
S. Sekya and Y. Kikuchi. The Eruption of Bandai-San, Trans. Seismological Soc. Japan, Vol. 13, 1890, pp. 140–222.
N. S. Shaler. Volcanoes, Aspects of the Earth, New York, 1904, pp. 46–97.
N. S. Shaler and R. S. Tarr. Dikes of the Cape Ann District, Massachusetts, 9th Ann. Rept., U. S. Geol. Survey, 1889, pp. 579–602.
G. O. Smith. Geology and Physiography of Central Washington, Prof. Paper 19, U. S. Geol. Survey, 1903, pp. 1–39.
G. J. Symons, J. W. Judd, and Others. The Eruption of Krakatoa and Subsequent Phenomena, London, 1888, 494 pp.
R. S. Tarr. A Recent Lava Flow in New Mexico, Amer. Naturalist, Vol. 25, 1891, pp. 524–527.
T. Thoroddsen. Volcanoes of Iceland, Petermanns Geog. Mitteilungen, Vol. 153, 1911, pp. 108–111; *ibid.*, Vol. 51, 1905, pp. 1–5.

S. von Waltershausen. Der Aetna, Leipzig, 1880, 2 vols., 371, 548 pp.
Zeitschrift für Vulkanologie, Naples, Vol. 1, 1914, to date.

TOPOGRAPHIC MAPS

Volcanoes

Flagstaff, Ariz.	Lassen Peak, Cal.	Shasta, Cal.
Livingston, Mont.	Mt. Taylor, N.M.	Marysville Buttes, Cal.
Crater Lake Special, Ore.	Island of Kauai, Hawaii	Chitina, Alaska, 601 A

Laccolites

Henry Mountains, Utah	Sturgis, S.D.	Spearfish, S.D.

Lava Plateau

Spokane, Wash.	Bisuka, Idaho.	Ellensburg, Wash.

Trap Ridges and Palisades

Springfield, Mass.	New Haven, Conn.	New York City Special

CHAPTER XIV

PLAINS AND PLATEAUS

Nature and Origin

The simplest of land forms is the *plain*, and it is by far the most widespread topographic feature on the earth. Much the greatest portion of the ocean bottoms is occupied by plains, and a large proportion of the continent surfaces as well.

A plain is a level or gently undulating portion of the earth's surface, and it is usually, though not always, underlain by horizontal or nearly horizontal strata. In origin plains are most commonly the result of deposition of sediment, usually in water, and often in ocean water. Plains that have been formed beneath the sea have often been brought to a position above sea level by one of those changes in relative level of sea and land already studied. Very often they have been raised high above sea level, and are then commonly called *plateaus*, though this term has no real scientific significance, and in popular usage has no commonly accepted meaning. In general a plateau is understood to be a high plain, though it is common to speak of the *Great Plains* west of the Mississippi River, even where they are over 5000 feet above sea level, while lower areas west of the Rocky Mountains are called plateaus. On the other hand, some of the deep-lying plains of the ocean bottom are often referred to as oceanic plateaus.

Plains are formed by river, glacier, lake, and ocean deposits and by volcanic outflow; they are also formed by denudation, as when a surface is worn to the state of old age, or when a river, swinging back and forth, planates the surface. Naturally, therefore, there are numerous differences among plains from the standpoint of their origin or structure. There are also differences according to the process by which they are being modified, and their stage in the erosion cycle; for, like all land surfaces, plains exposed to subaërial denudation undergo a cycle of dissection. Starting level, they may be sculptured into a hilly state, and then, with the approach of old age, they tend again toward levelness.

Different Types of Plains

River Plains. — In the chapter on rivers the nature and origin of river plains has been stated with such fulness (pp. 143–168) that we need merely call attention to the fact that they are to be classified in this group of land forms. The chief plains due to river action are

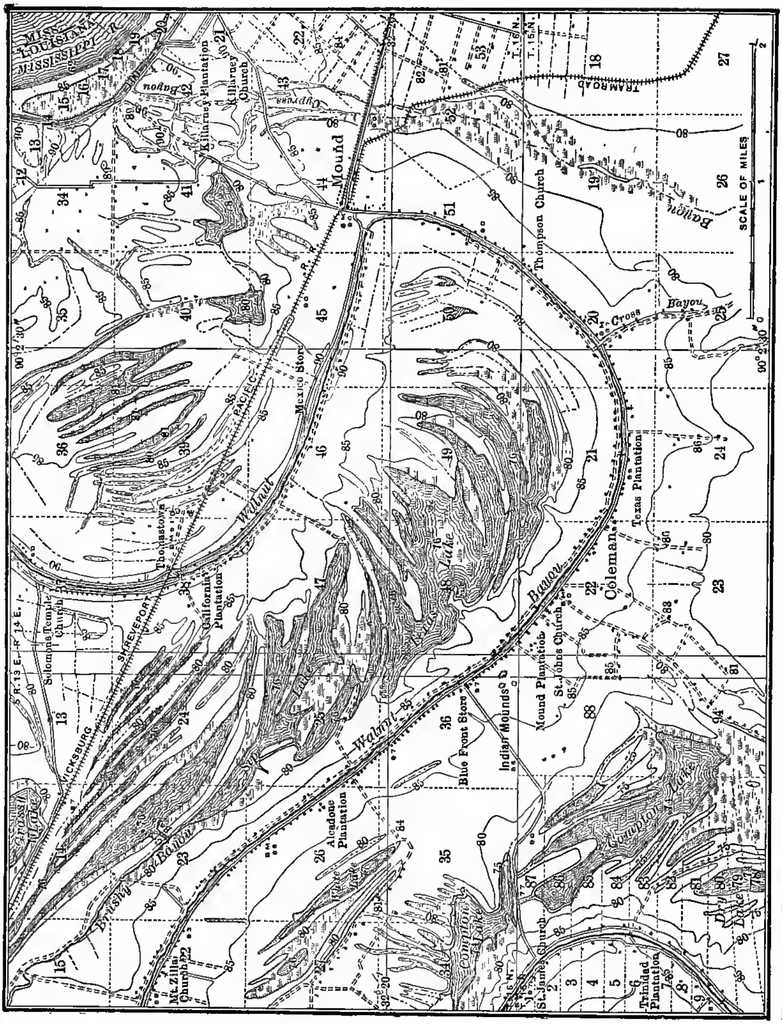


FIG. 328. — Topographic map of part of the floodplain of the Mississippi River in Louisiana. Contour interval five feet. Settlement limited to the natural levee, as on Walnut Bayou. (Mound Quadrangle, U. S. Geol. Survey.)

floodplains (Fig. 328 and Pl. III), terraces, deltas, broad, flat alluvial fans, and deposits in partly or completely enclosed mountain valleys. Perhaps to these might be added the outwash gravel plains built up by streams issuing from glaciers (Pl. IV).

Glacial Plains. — Where glaciers have spread out over gently undulating surfaces their deposits have sometimes filled valleys and made the land more level. This is in places done (*a*) by deposits directly from the ice, making *till plains,* (*b*) sometimes by deposits made by water from the melting glacier, and very often by the two combined. Large tracts of country in the northern Central States have been levelled up in this way. In places the deposits are several hundred feet in depth, and were all the glacial drift removed, this region would be far less level than now.

The ice of large glaciers also builds up plains or plateaus. Thus the piedmont Malaspina Glacier is a low-lying plateau; the Greenland ice sheet is a vast ice plateau; and the Antarctic ice sheet is a still greater one.

Lava Plains. — Lava flows, spreading out at the base of a volcano, or still more notably when flowing from fissures, may give rise to plains. This finds illustration in the Columbia River valley of Washington, where flow after flow of lava has not only filled valleys, but has even caused the burial of mountains, transforming a hilly and mountainous country to a level or undulating lava plateau of great extent. The plateau of the Deccan in India and the Icelandic plateau are other instances of lava plateaus.

Volcanic ash, falling upon the country round about a volcanic vent, may also level up the surface, though wind and running water are aids in the building of such a plain. The country near Vesuvius is an instance of a plain of this origin.

Lacustrine Plains. — Sediment settling upon a lake bottom tends to smooth over irregularities and gradually to form a level bottom. If such a lake disappears, a plain is left on its site, as in the case of the valley of the Red River of the North, in which the great Lake Agassiz formerly stood. If a lake persists, it will in time become completely filled and its site will then be occupied by a *filled lake plain.* Thousands of instances of this are found in the regions of former glaciation, where the filled lake plains are still so level that they are swamps.

During the stages of lake filling, smaller plains are also formed around the shores. In some cases a narrow plain is cut by the waves as they eat into the land; in others the shore is built outward, forming a swampy plain strip at or near lake level. Larger plains are formed by the filling of bays, and by the growth of deltas into the lake.

Marine Plains. — Along ocean coasts there are also narrow plains formed by wave cutting, as in the submerged offshore platform that extends seaward from exposed headlands. There are filled bays also, and delta plains, and swampy coastal strips in protected parts of the shore, — the salt marsh plains.

As in the case of lakes, the sediment borne to the sea is strewn over the sea floor, tending to level it by filling the depressions and by smoothing over the elevations. Far from the coast the settling of organic remains to the sea floor has had a similar effect. The tendency is, therefore, to make plains of deposit, even where the sea bottom has been roughened by diastrophic movement. It is partly because of this process that such vast areas of the ocean bottom are plains; though doubtless here, as on the land, there are great tracts which have not been deformed by diastrophism or roughened by vulcanism. The sea floor is narrower, protected from the roughening effect of denudation.

Where a part of the ocean bottom is brought above sea level, unless this is accompanied by pronounced deformation, it is normally added to the land as a plain. This is why so many coasts in regions of recent uplift are bordered by *coastal plains*, as in the case of eastern North America south of New York. Uplift along the western coast, being accompanied by crustal deformation, has resulted in mountain formation; but even here strips of coastal plain are present where the sea bottom has been raised without folding or faulting.

Plains of Denudation. — As a land surface is worn down by denudation, plains are caused not only by deposit but also by the direct attack of the agents of denudation. Instances of this have already been mentioned as a result of wave work along lake and sea coast. The lateral cutting by a river, as illustrated in terrace formation, is another.

Plains also develop as denudation lowers a land surface. This is best illustrated in areas of nearly horizontal strata as a result of the fact that resistant beds are removed less readily than weaker ones. Therefore, when such a resistant bed is reached by subaërial denudation, it tends to hold the surface at that level while the weaker strata are stripped away. Since the layer is horizontal the surface to which it gives rise is more or less level, that is, a plain. The nature of the process and the resulting topography are more fully considered in the discussion of the dissection of plateaus. These plains may be called *plains of differential gradation*.

If a land surface continues to be reduced by denudation, it is ultimately worn down so near to baselevel that it approaches the condition of a plain, even though in its initial state it was mountainous land. Such a surface has been given the name *peneplain*, or almost a plain. Former peneplains (Pl. X), now uplifted or dissected, are found in many places. Some of them were at an earlier period interpreted as *plains of marine denudation*, but it is now believed that extensive plains of this origin are not common, if indeed they are present at all. The coast line appears to be too unstable to prevent their development, and though the zone of wave attack is one of great activity, it is confined to a very limited area, compared to that upon which subaërial denudation is at work.

Constructional and Destructional Plains. — A simple classification of plains, upon the basis of origin, is to consider them as a result of (1) constructional processes, (2) destructional processes. Those plains made by deposit — fluviatile, glacial, volcanic, lacustrine, and marine — are constructional in origin. Those shaped by the degradation of the land, as outlined in the preceding paragraph, are of destructional origin. Of these the peneplain and the plain of differential gradation are most common and most important.

The Life History of Plains and Plateaus

Dissection of Plains. — In its initial stage a plain has a level surface, often so level that water does not freely drain off. This is true on

Fig. 329. — The plain of the valley of the Red River of the North, the bottom of glacial Lake Agassiz.

parts of the coastal plain in southern Florida and on the Texas coast; it is true of plains of other origin, as in the swampy plains of filled lakes and on deltas and floodplains. Such a plain is a young plain, and, because of its swampy nature, it is not suited to human occupation and it is usually a wilderness of luxuriant plant growth. In the tropical zone the dampness favours the development of tropical diseases and the plains are even dangerous to cross. Rice culture in the South and cranberry culture in the North are about the only industries that are favoured by such conditions in United States, though forest products are obtained in some parts, and peat is taken from some of the swampy lake plains of the North.

If such a plain is elevated high enough above baselevel so that the streams are enabled to cut along their beds, the surface begins to be dissected. First there are narrow young valleys, with broad, flat-topped divides between, as in the plains of the Red River of the North in North Dakota and Manitoba (Fig. 329). If the soil is good, such a surface may become the seat of successful agriculture, for the land is level and drainage is provided for by the stream courses. A little later, when steep-sided gorges are sunk below the plain level, conditions begin to be slightly less favourable.

Thereafter, the plain will pass through the various stages of youth maturity, and old age, if there is no accidental interference with the cycle of development. Exactly what the successive stages will be depends upon several factors of which three — rainfall, elevation, and rock structure — are the most important. Each of these is so fundamental that it has a dominating influence on the land forms of the various stages in the cycle of dissection.

Influence of Uniform Rock Structure. — Assuming the simplest conditions for the basal consideration of the cycle development we may start with a plain of uniform rock structure, at a moderate elevation, and in a region of moderate rainfall. Here the cycle of development consists first of the development of a few gorge-like valleys with intervening flat-topped divides; then the increase in number of such valleys by gnawing back at the headwaters, thus narrowing the divides; accompanying and succeeding this stage, a broadening of the valleys and a lowering of the inter-valley tracts, thence on to the stage of old age. Thus the plain passes (1) from a level surface, (2) to a level surface crossed by gorge-like valleys, (3) to an undulating, hilly country, and (4), by a lowering of the inter-valley tracts, back toward the condition of a plain in old age.

No matter what the elevation, rainfall conditions, and rock structure, the cycle of development of plain from youth to old age passes through essentially these stages, but with notable variations in topographic form in accordance with their influence.

Influence of Complex Rock Structure. — Considering first of all the influence of rock structure, we will assume exactly opposite conditions from those first stated; that is, instead of uniformity of rock structure, a high degree of complexity, such as exists in a peneplain produced by the reduction of a mountain region to the condition of old age in a first cycle. Here rocks of various degrees of resistance stand at all angles. With the dissection of such a plain in the second cycle the surface form in the successive stages is influenced, not merely by the denudation, but also by the structure and attitude of the underlying rocks. Instead, therefore, of a symmetrical series of valleys and hills, developed by the operation of denudation alone and uninfluenced by variations in the underlying rock, a topography is developed in which the rock structure and attitude dominate the topography. Ridges and parallel valleys may develop and a truly mountainous topography may be etched out in the varying rocks, especially in the stage of maturity. In old age, however, when the influence of underlying rock becomes lessened, even such a surface tends toward the plain.

Influence of Alternate Weak and Resistant Strata. — Intermediate between these two extremes there are all conditions of variability in rock structure beneath plains. By far the most widespread is the variation in degree of resistance in the nearly horizontal strata. Until rivers have cut into these layers this difference is not revealed and exposed to denudation, but when alternate layers of strata of different degrees of resistance are exposed, they commence at once to influence the rate of denudation and, therefore, the topography. This influence first expresses itself along the bottoms of the streams, giving rise to rapids and falls, and along the valley sides, to rock terraces. Each resistant layer wears back at a slower rate than the less-resistant strata, and, therefore, tends to stand out more boldly.

Tablelands. — As such a plain passes from youth to maturity the differences in rock structure, if great enough, may dominate the topographic form. This is brought about in two ways: (1) by retardation of vertical denudation, (2) by horizontal recession of cliffs. The first gives rise to level tops, the second to steep cliffs. The term *tableland*, often used as a synonym of plateau, is derived from these topographic features, which are commonly well developed in such high plains. The Spanish word *mesa*, which means table, refers to a specific table area in a land of table top forms. A mesa is a flat-topped surface terminated on some or all sides by a steep face or *escarpment*. A smaller area of similar form is called a *butte*. Both buttes and mesas so abound in many plateau lands as to have suggested the term tableland.

In buttes and mesas, and in less well-defined level surfaces faced by escarpments, there is a general similarity of conditions. The level top is underlain by a resistant stratum nearly or quite horizontal in position, and it is so resistant to the general lowering of the surface by denudation that a table form results. If it is worn away, denudation will proceed more rapidly in the underlying weaker strata until another resistant layer is encountered lower down, when the rate of denudation will once more be halted and a table top surface be developed at the lower level. Accordingly as the surface wears down, table forms appear at different levels. Thus in crossing a plateau one may go from one level to another, each time ascending or descending an escarpment that separates the two levels; and one may be certain that when the surface of an upper level is lowered, it will be halted at the next lower level of resistant rock, and that, at an earlier stage, the site of the higher levels was occupied by a table top at a greater elevation.

The mesas, buttes, and other table top areas are wasting away, partly by a general lowering of their surfaces, but even more effectively by the wasting back of their bordering escarpments. The underlying weaker layers crumble on exposure to the air and to underground water, the edge of the overlying resistant layer is slowly undermined, and fragments fall down the escarpment face, to be removed by running water or by wind, or perhaps, after further disintegration, by weathering. This process of undermining of an escarpment face has been spoken of as *sapping*. By the operation of sapping, cliffs are made to recede and thus the table top areas are steadily diminished. The recession naturally starts from the sides of valleys cut into the horizontal strata, and the escarpments may be pushed back many miles. Similar recession of cliffs may start from fault scarps as well as from stream-cut valleys.

The rate of recession of cliffs under the process of sapping will vary greatly with difference in resistance of the strata, thickness of strata, and rate of removal of the fragments that fall from the cliff face. In western United States, where such cliff recession is illustrated in a multitude of buttes, mesas, and other table top, escarpment-faced areas, some of the most striking instances are where lava rests upon unconsolidated or partly consolidated clays. There the escarpments are strongly developed, and at the base of the cliff are many blocks of lava, while the surface back of the escarpment is broken and fissured by cracks developed in the process of undermining through sapping. From such extremes there are all gradations to faintly developed scarps where layers are thin or where differences in resistance are slight.

Belted Plains and Cuestas. — The strata underlying plains are often inclined at a low angle, thus bringing successive layers to the surface. This is well illustrated in the coastal plains of eastern United States, where, passing from the coast inland, one finds layers of different kinds rising to the surface and dipping gently seaward. This gives rise to belts of different soils, some sandy, some clayey, extending roughly parallel to the coast. In consequence there are cultural belts also, dependent upon the soil conditions.

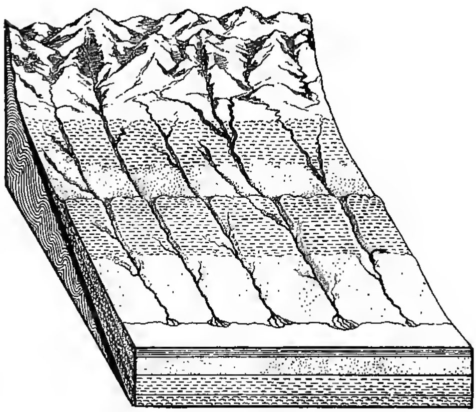


Fig. 330. — Block diagram of a belted coastal plain.

Since these outcropping strata also vary in resistance, they give rise to topographic belts also, as the surface is slowly worn down. The weaker strata wear fastest, leaving the more resistant layers at a higher level, and giving rise to a *belted coastal plain* (Fig. 330). Since the strata have a seaward dip, the surfaces of the more resistant layers slope gently toward the sea. On the landward side there may be a steep slope, and the resistant layer may even end in a low escarpment, which is slowly receding in the direction of the dip by the operation of sapping. The name *cuesta* has been given to such a land form, with a steep face on one side and a gently sloping surface on the other (Fig. 331). Like the word *mesa*, this is a Spanish term. It is applied

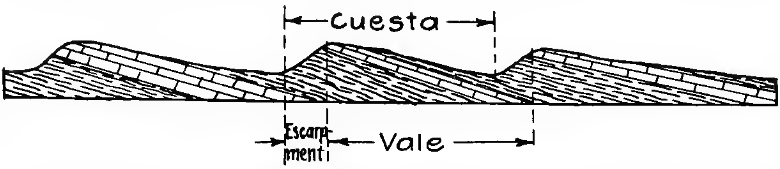


FIG. 331.—Cross-section to show the relation of cuestas to rock structure and the use of the terms *escarpment* and *vale*. (After Veatch.)

in New Mexico to low ridges with a steep slope on one side and a moderate slope on the other. Cuestas are well developed in Louisiana, Alabama, the Paris basin of France, etc.

The drainage of a belted coastal plain may be perceptibly influenced by the etching out of the layers. On a coastal plain the normal drainage is seaward, down the slope of the plain, some of the streams extending out over the plain from the land, others developing on the plain between these extended streams. As the surface wears down, however, subsequent streams develop in the valleys along the outcrop of the weaker layers, on the inner face of the cuestas. These subsequent stream courses extend approximately at right angles to the direction of the consequent streams, which they enter as tributaries; and to them obsequent tributaries flow down the cuesta scarp, thus flowing in the direction exactly opposite to the original consequent course.

A belted arrangement is also developed during the denudation of inland plains, some of them far from the sea and not to be classed as coastal plains, though in their inception far back in geological time they may have risen above the sea as coastal plains. In these ancient plains the strata are consolidated, and the differences in resistance to denudation may give rise to pronounced topographic forms. There is such an arrangement of belted uplands and lowlands in Wisconsin from the shores of Lake Michigan northwestward to the highland of crystalline rocks which occupies the northern part of the state. Another case is in Ontario and western New York. To the north are crystalline highlands and, bordering it, a lowland in weak strata, in a part of which Lake Ontario lies. South of this is an escarpment where the Niagara limestone outcrops, and back of it another plain in which Lake Erie lies, while beyond this rises another escarpment, the northern edge of the Allegheny Plateau, or, as it has been called, the Allegheny cuesta. Neither this nor the Niagara cuesta has any persistent inclination of the surface away from the escarpment, although the strata dip that way. A second process has, however, operated in this region, the glacial agency following the normal stream agency. Similar belted plains and plateaus are very common in other parts of the world, as in eastern England and north of the Colorado River in Arizona. They grade into the tableland type of topography discussed above.

Effect of Elevation. — In the dissection of a plain it is manifest that there must be great difference in the resulting form, according to altitude. A high plain, or plateau, offers opportunity for the development of gorges and canyons; and the depth of dissection reveals many different strata, so that there is ample opportunity for the exposure of cliff-making strata. In the wearing down of such a surface, therefore, the stages of youth and maturity are marked by the cutting of canyons, the recession of cliffs under the influence of sapping, and the development of buttes, mesas, and other table topped areas.

Regions of lower altitude offer less opportunity for the production of such forms, which are really characteristic of plateaus; yet they are not entirely absent. Gorge valleys, mesa-like forms, miniature buttes, and well-defined escarpments are developed in the course of dissection of even low plains of variable horizontal strata. They are merely less numerous and less striking features in the dissection of a plain of low elevation.

A high plain may be so cut up by dissection during the stage of late youth or early maturity that it is transformed to a maze of hills and valleys. It may even become so dissected as to simulate mountain topography, and win the name mountain. This is the case in the Catskill Mountains of New York, which are really nothing more than a much-dissected plateau of nearly horizontal strata. If the strata are not greatly different in their degree of resistance to denudation, the hilltops may become rounded, and, in the absence of pronounced cliff-making strata, the valley slopes may be fairly smooth. Then, as in the case of the Allegheny Plateau of central New York, the maturely dissected plateau may become a hilly region, with few flat-topped areas, no typical mesas and buttes, and few escarpments. In the plateau in question the only escarpment of prominence is that which forms its northern face, where relatively resistant limestone outcrops. This escarpment in one place has developed a slope so steep as to give rise to the local name Helderberg Mountain. The effect of the glacial accident in this plateau is not, as yet, well worked out.

Where the strata are variable in degree of resistance, the effect of the cliff-making layers on the topography is very pronounced, and flat-topped areas and escarpments abound.

Effect of Climate. — The angular forms developed by the excavation of canyons and by the recession of cliffs appear in far greater perfection in arid than in humid climates. This is because (1) weathering is less active, or mechanical disintegration more active, in arid regions, so that there is less tendency to round the angular forms: (2) the wind action in arid regions removes the disintegrated fragments and thus leaves the bed rock more exposed; (3) vegetation cover is less extensive in arid climates, and thus exerts less influence in holding the disintegrated fragments where they fall; and (4) the general lack of vegetation obscures the angular forms less in arid than in humid regions. Thus a cliff fifty feet in height may be quite hidden from general view in a forest-covered region, while in an arid country it would stand out with full prominence. It is true also that most high plateaus in the world, in which angular forms are most rapidly developed, are located in arid regions.

Accordingly dissected plateaus in humid regions, while not lacking escarpments and table-topped areas, are not so characterized by them as are dissected plateaus in arid regions. Rounded slopes are common and even dominant in the one case, and angular forms characterize the other, largely as a result of differences in the climatic conditions under which they have developed.

Relation of Plains and Plateaus to Human Life

Dense Settlement upon Plains. — It is upon the plains of the world that the greatest part of the human population is found. Because of the levelness, soil is not readily washed off, and it is, therefore, commonly deep and often fertile. In many cases, too, the plains are made of transported sediment of fine grain and fertile character, as in the case of floodplains, deltas, and abandoned lake bottom plains. Such level surfaces often contain a large admixture of humus, often so much that they are quite black in colour, and consequently very fertile, the humus being due to the luxuriant growth of plants upon the plains, and often to swampy conditions on the level surface, as a result of which the humus is protected from loss by decay.

Agriculture is encouraged also by the levelness of the surface, which makes farming operations easier, and aids in the construction of highways for transportation of products. Very often, too, plains are crossed by streams in which the slope is so gentle that they are navigable, thus further aiding in transportation.

Plains occupied by an agricultural population are so numerous that it would be a long list if all were mentioned. Among them are included the plains of the Mississippi valley; the plains of France, Belgium, Holland, and northern Germany; the Hungarian plain; the Russian plains; the delta plain of the lower Nile; and the deltas and floodplains of India and China.

Kinds of Plains Unfavourably Situated. — Some plains are too swampy for occupation, as already stated; some have a poor soil, like the sandy soils of parts of the Atlantic coastal plain; and there are some with too dry a climate, or so far north that the climate is too cold, as in northern Canada and Siberia. High plains are sometimes so lofty that their climate is unfavourable to settlement, as in parts of Tibet; but elevation is at times beneficial. For example, the Colorado plateau, in an arid region, rises high enough in places for forest growth; and part of the Columbia lava plateau of Washington receives rainfall enough for agriculture because of its elevation. In tropical countries elevated plains and plateaus are often high enough to give rise to temperate conditions in a zone where otherwise the tropical heat would prevail. A large portion of the settlement of the tropical parts of the New World and of Africa is to be found upon high plains, above the level of torrid heat.

Young plains, if so immature and so low that their drainage is retarded, are unfavourable to settlement. As the cycle of denudation proceeds, the surface becomes more irregular, and, if low, they may become and remain habitable throughout the cycle. If the plains are high, dissection may transform the surface to such a degree of ruggedness that density of population is discouraged. This finds illustration in the much-dissected plateau that fringes the western base of the Appalachian Mountains, a rugged, hilly region of sparse settlement, in the main, with little agricultural industry, still largely covered by forest, and now, as hitherto, a barrier to travel.

Plains and Plateaus of the United States

Typical Plains. — Plains occupy so much of the land surface, and their general characteristics are so alike in the different continents, that it does not seem necessary to enter into a consideration of the characteristics of plains in various parts of the world. A brief description of the features of the plains and plateaus of the United States, which include all the main types, will give an adequate idea of the characteristics of plains in general. This description, which is, in part, in the nature of a summary, will commence with the eastern part of the country and proceed westward (Figs. 332, 339).

The Coastal Plains. — Off the eastern coast of United States there is a level sea bottom plain, known as the *continental shelf*, sloping seaward at the rate of 5 or 6 feet per mile. If there should be an uplift of 600 feet, this very level plain would be added to the continent. The surface of the plain would be very level, and it would be underlain by unconsolidated sediments.

Such has been the actual history of the region south of New York at a recent period; for, by change in the relative level of the land and sea, a part of the sea bottom has been brought above sea level, forming the coastal plains which skirt the eastern coast from New York to Mexico and beyond (Fig. 333). These plains are, in general, level, they incline gently seaward, and they are underlain by nearly, or quite, unconsolidated sediments. At the coast line the plains extend with no noteworthy break beneath sea level, for they are continuous with the continental shelf. The line of separation is marked by sand bars and other coastal forms, and the coast line is somewhat irregular because of recent slight subsidence, as in Chesapeake Bay.

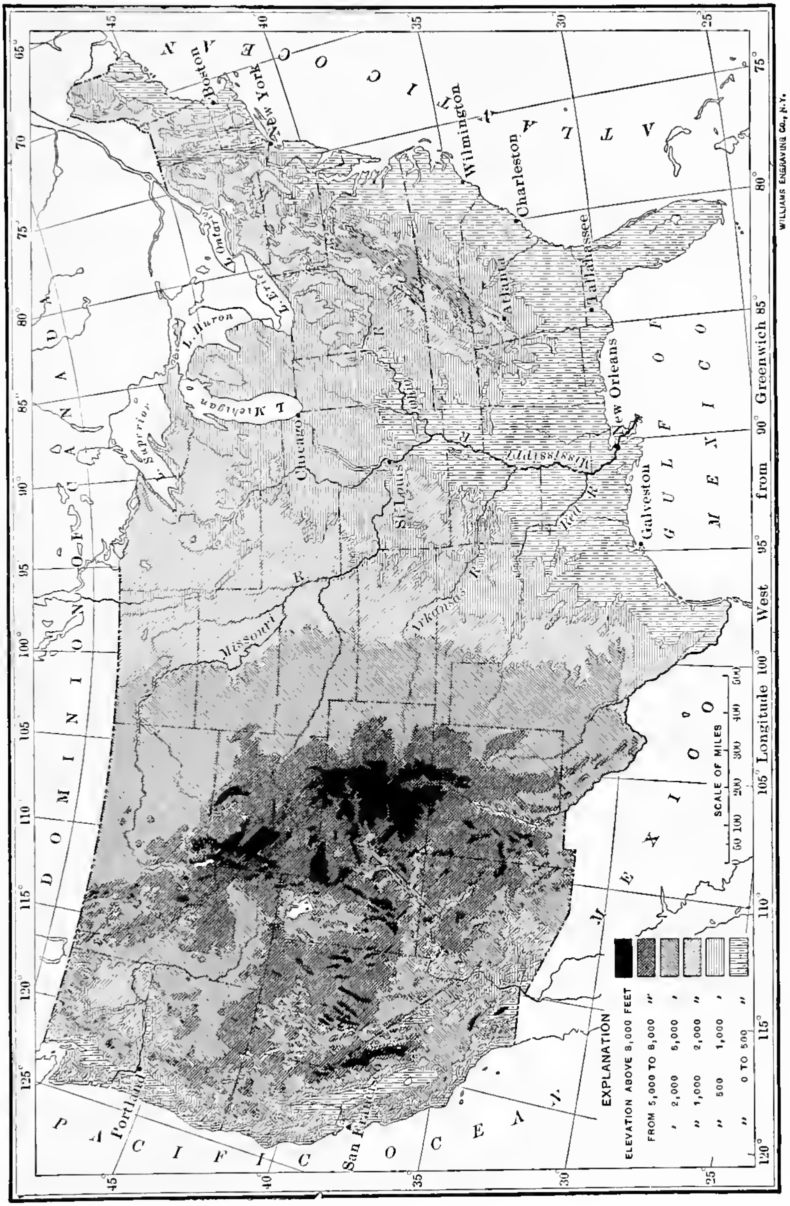


FIG. 332.—Topographic map of the United States. (Henry Gannett, U. S. Geol. Survey.)

In parts this plain is so level that it is swampy, and some of the outer portions, as in southern Florida and between Galveston and Houston, Tex., have been upraised so recently that the fossils entombed in the sediments are of the same species as those still living in the neighbouring waters. Even the irregularities of the former sea bottom are preserved and give rise to lower ridges and depressions, the chief topographic features of the new land. Farther inland the plains have been longer exposed, they are higher, and, consequently, they are somewhat dissected by the extended and consequent streams which flow seaward over them. These streams have sluggish flow, and the larger ones are navigable; their valley walls are prevailingly low and sloping, being composed of unconsolidated sediment; and, in their lower courses, the tide enters, and the streams are bordered by swamp lands, through which they flow in meandering courses.

FIG. 333. — The level coastal plain in Florida.

These coastal plains are not densely settled. Part of the region is too swampy, especially along the coast; but, here, there is some rice cultivation, and there are forests of cypress and other trees, adapted to growth in swampy land. Farther inland much of the soil is too sandy for successful agriculture, and the plains are covered by a pine forest, from which much lumber, as well as tar and turpentine, are obtained. There are belts of clay and other more fertile soils, and, on these, cotton and other crops are raised. The inner margin of the coastal plain is ordinarily dissected into a low, undulating, hilly land, in places 400 to 600 feet above sea level, and a hundred miles or more from the sea.

Still farther inland the plains end against the old land, a low hilly surface known as the Piedmont Plateau, an ancient mountain region now worn to a surface of low relief. Doubtless the source of much of the sediment of which the coastal plains are made was this old land, during the period of its reduction by denudation. The Piedmont Plateau from New Jersey to Texas is covered by a fertile residual soil, and is the seat of extensive cotton culture.

At the boundary between the Piedmont Plateau and the coastal plain the streams are so commonly interrupted by rapids and falls that their line has been called the *Fall Line* (Fig. 334). The rapids and falls are due to the fact that the streams have been able to cut more rapidly into the unconsolidated sediment of the coastal plains than in the resistant crystalline rocks of the Piedmont Plateau. Because of the water power, and because navigation is checked here, the Fall Line is the seat of a chain of towns and cities, including Trenton, Philadelphia, Baltimore, Washington, Richmond, Raleigh, Columbia, Augusta, Macon, and Montgomery. Thus the coastal plains are bordered by a chain of towns and cities along the inner margin, and back of them is a fertile agricultural region. While the plains themselves are, in the main, sparsely settled, traffic across them by rail and stream from the Piedmont Plateau to the sea is important, and, over such a level surface, railroads are easily built. Because of this traffic the coastal plains are bordered on the outer side by a chain of sea coast towns, including Norfolk, Wilmington, Charleston, Savannah, Mobile, and Galveston, situated on harbours that are, in general, poor and partly obstructed by sand bars. Most of these harbours are shallow bays, formed by the slight submergence of the level land, admitting the sea into the coastal plain valleys.

FIG. 334.—The Fall Line and its cities.

Allegheny Plateau. — Bordering the Appalachian Mountains on the west is a plateau (Fig. 335), extending from the Hudson River southward to Alabama. Near the mountains it is high, and usually higher than the mountains themselves; but its surface descends toward the western and northern margins, merging into the plains of the Mississippi valley, and terminating in an escarpment on the east, and in New York, on the north. The plateau is so high and so rugged that it has been called the Allegheny Mountains in the central part, the

Catskill Mountains on the northeastern end, and the Cumberland Mountains on the southern end. The names Allegheny Plateau and Cumberland Plateau are preferable. The surface rises to an elevation of 2000 or 3000 feet, and in the Catskill Mountains to an elevation of over 4000 feet.

In this plateau the strata are nearly or quite horizontal, quite in contrast to the complexly folded strata of the Appalachian Mountains. Standing high above baselevel, there has been ample opportunity for

FIG. 335. — Allegheny Plateau along the New River, W. Va. (Hillers, U. S. Geol. Survey.)

the streams to sink their channels deeply into the plateau, and, therefore, valleys 1000 to 2000 feet in depth have been cut. But, since the stage of denudation has passed that of early youth, the valleys are not prevailingly steep-walled gorges and canyons, though locally there are precipitous slopes and even gorges. In general the slopes have wasted back so that, although steep, they are usually capable of supporting fairly continuous forest growth, and in many parts have been cleared for pasture or for tillage, especially in the glaciated northern part of the plateau in New York and Pennsylvania.

There are flat-topped uplands, often cleared for farming, while the valley slopes are left in forest; but butte and mesa topography is not typical of the region. Here and there some unusually resistant layer stands out as a cliff, traceable along the valley walls, but there is no such angularity of topography as characterizes arid plateaus. This is due to a combination of several causes: (1) the advanced stage of dissection, (2) the humid climate, (3) the protecting and obscuring influence of forest cover, (4) the uniform consolidation of the layers and the scarcity of exceptionally resistant beds.

In early days the Allegheny Plateau was an even more important barrier to travel from the coast to the interior than the Appalachian Mountains proper. It still presents serious obstacle to road and railway building. A large part of the plateau is still forest-covered, and, even where cleared, farming is limited in amount and value. Many of the slopes are too steep for farms, and the more level uplands are separated from the valleys by such steep slopes that roads are poor, difficult to maintain, and hard to draw loads over. Even the valleys are ordinarily sparsely settled, and upland areas are often remote from markets. These conditions find their best expression in the plateau of eastern Tennessee and Kentucky, where there are people who have had such slight contact with the outside world that they preserve customs of the early day when settlers first occupied the plateau land. They still wear homespun, they resist the government laws against illicit distilling, and they take the law in their own hands in settling disputes and feuds. Farther north there is a less degree of isolation.

Were it not for the fact that this region must be crossed by westbound railways, and that valuable mineral wealth exists in the horizontal strata, the Allegheny Plateau would be much more isolated and sparsely settled than it is. Coal is found in many places, often revealed in the sides of the deeply cut stream valleys; petroleum and natural gas are also found; and iron ore is present in some beds. The exploitation of these products has caused influx of people in parts of the plateau.

The only large city in the Allegheny Plateau is Pittsburg, whose growth has been due to mineral wealth and to a situation at the junction of the Allegheny and Monongahela rivers, which unite to make the navigable Ohio River. Other centres of industry are located on the Ohio and on the railway lines that cross the plateau, especially in the broader valleys.

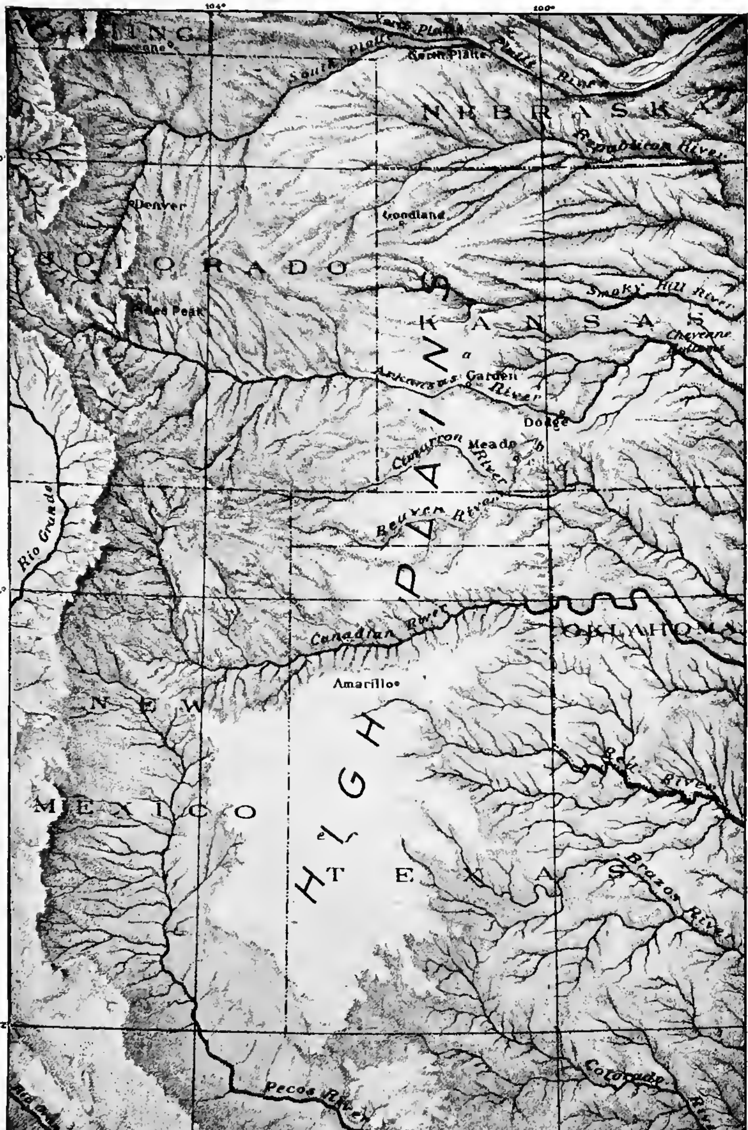
The Mississippi Valley Plains. — From the Allegheny Plateau the surface slopes downward gradually, and fairly regularly, to the Mississippi, then westward it slopes up to the Great Plains and the base of the Rocky Mountains. This great area of plains, one of the largest in the world, is interrupted only by the low mountain areas of central Texas, Oklahoma, and Arkansas, the highland region around the western end of Lake Superior, and the Black Hills.

It is not a single plain, of single origin, but such a complex of plains that it will not be possible here to refer to more than a few of the more important divisions. In the south it merges into the coastal plains; along the rivers it is crossed by strips of floodplain; while there are delta plains at the river mouths, notably the Mississippi. In southern Missouri and northern Arkansas the plains rise to form the low Ozark Plateau, which has been interpreted as a trans-Mississippi extension of the Allegheny and Cumberland plateaus, which it resembles in important respects. Toward the west the plains become gradually more and more arid, and rise to true plateau elevation in the Great Plains (Fig. 336). In the southwest they may have been partly modified by wind work. In the north their topography is modified and often even entirely made by glacial deposits or by deposits made in front of the glacier, for instance, the lacustrine silts of the Red River of the North, laid down in the bed of the ice-dammed Lake Agassiz.

The underlying strata of this great series of plains are nearly horizontal sediments, consolidated into hard rock layers, but worn down to a condition of low relief, during a long and varied series of erosion cycles. It has been classed as an ancient coastal plain, or series of coastal plains, added to the continent in long-past geological time, and greatly denuded. Low escarpments still stand out and a belted arrangement of outcropping strata locally forms cuestas, as in Wisconsin, and affects both soil and topography. Where highest, as in the Allegheny Plateau, in the Great Plains, around the Lake Superior highland, especially in the Driftless Area, and in the Ozark Plateau, the plains are so dissected that the topography is hilly; but in the Great Plains the dissection has assumed the arid land type of angular form. Here one finds frequent escarpments, canyon-like valleys, and mesa forms, especially near the Rocky Mountains. Some areas of the Great Plains near the base of the Rocky Mountains have been levelled up by deposit of sediment washed down from the mountains and spread out by the streams at their base.

Within the area of the Mississippi valley plains, the deposits, deepest in the valleys, have in general tended to still further level this portion of the plains. In fact, over considerable areas these deposits have formed so level a surface that water did not drain off naturally, and, therefore, extensive tracts were too swampy for tree growth when first seen by white men. These *prairies*, now drained, sometimes have a black, fertile soil because of the abundant organic matter, and are among the finest agricultural lands. It is probable that other prairie areas were formed, or extended, by fires set by the aborigines.

As far west as the 100th meridian, the larger part of the Mississippi valley plains is occupied by an agricultural population, making this one of the leading farming regions of the world. It is the granary of the United States. Only limited areas are too hilly or too swampy for cultivation. With abundant coal and other mineral resources, and with excellent transportation facilities, it has developed varied manufacturing industries, and is the seat of large and flourishing cities. West of the 100th meridian these advantages are lacking, and the arid plains are given over to ranching, and only small towns are found here and there. Agriculture is confined mainly to the valleys



THE HIGH PLAINS

Scale of miles: 0 50 100 150 200

FIG. 336.—A portion of the Great Plains. (W. D. Johnson.)

where irrigation is possible, or to those spots where artesian water can be obtained; but in the north, the agricultural belt extends a little west of the 100th meridian.

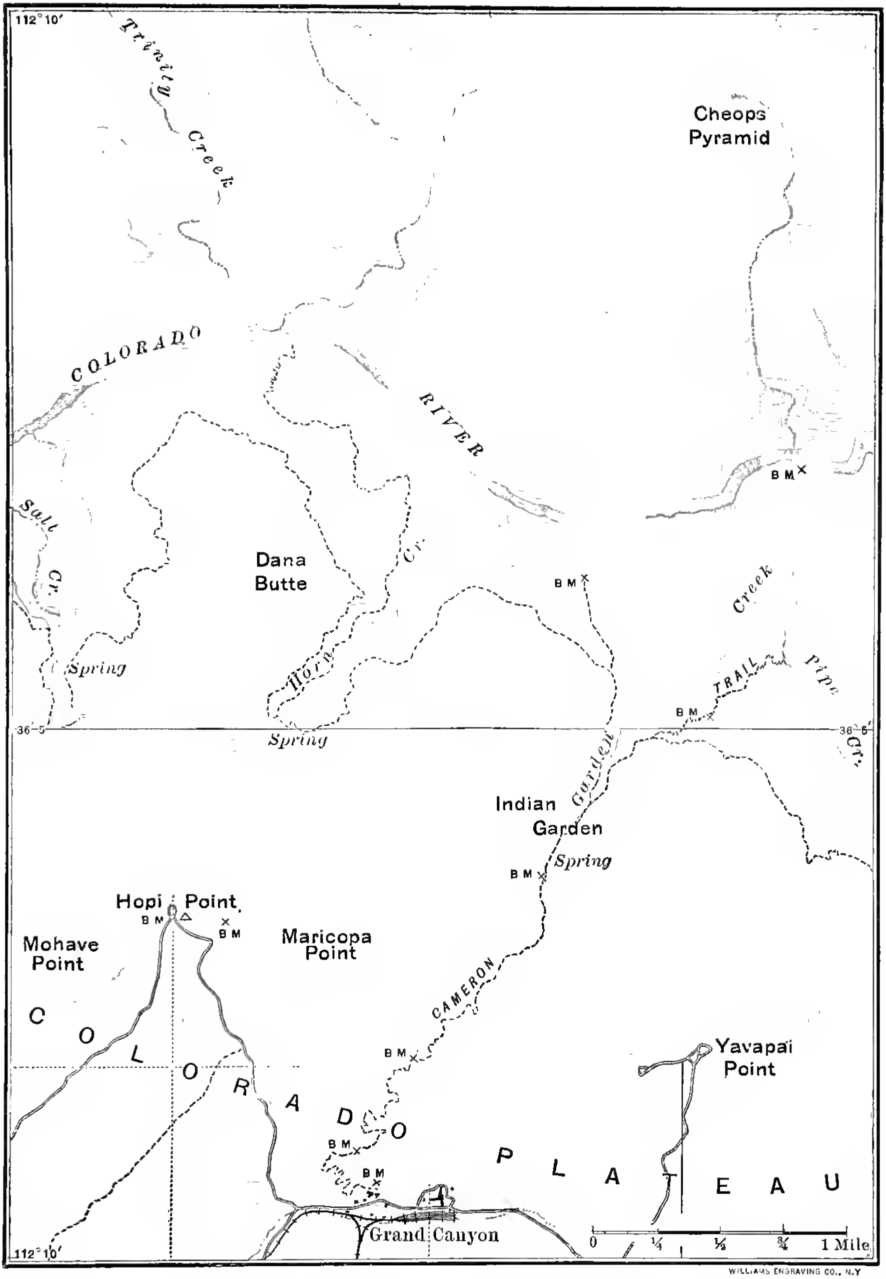
The Columbia Plateau. — A hilly and even mountainous land between the Rocky Mountains and the Cascade Ranges in Washington and Oregon and parts of neighbouring states was, as we have seen (p. 480), flooded with successive lava flows until the surface was built up into a lava plateau, far more level than the original surface. The lava sheets still retain their nearly horizontal position, though tilted locally. In these lava plains streams have cut their way, forming canyons, in some places of considerable depth (Fig. 337). Residual soil, formed by the disintegration of the lava, covers extensive areas of this plateau, and in parts of it there is rainfall enough for successful agriculture, notably wheat raising. On this plateau, and in the midst of the agricultural region, the city of Spokane has grown, the largest city between the eastern base of the Rocky Mountains and the Pacific coast.

The Columbia Plateau is a type of numerous similar, though smaller, lava plains in western United States.

The Colorado Plateau. — In Utah and Arizona is a great area of tableland, with elevations up to 7000 or 8000 feet. It consists of a series of plateau surfaces, ending in escarpments. The strata of the plateau are essentially horizontal, of varying degrees of resistance, and exposed to long and complex denudation. There has been faulting and some local tilting of layers, and volcanic action has built upon the plateau surface a large number of volcanic cones, one of which is the large extinct volcano known as San Francisco Mountain. Some of the volcanic activity has been very recent.

In the course of the denudation, deep canyons have been cut into the strata, and their walls are terraced by the differential denudation of the strata. Cliff-forming strata, revealed by faulting or by denudation, have receded and are still receding, giving rise to escarpment faces which separate the different plateau levels. There is a multitude of butte and mesa forms, especially in the neighbourhood of the canyons. It is a wonderfully sculptured land, a typical tableland, with the angular topography developed in such regions by denudation. Over most of the plateau the climate is so arid that forest growth is impossible, but in places the elevation is sufficient for the growth of an open pine forest. There are broad tracts with little soil and vegetation, but, over much of the surface, there is grass enough for cattle or sheep raising, though very often these industries are rendered impossible by the scarcity of water.

Into this plateau is sunk the Colorado River, in a canyon unsurpassed for grandeur among the valleys of the world (Pl. VIII). The Colorado, rising in the Rocky Mountains, receives an abundant water supply, which enables it to flow across the entire plateau region and the desert, to the Gulf of California. For 1000 miles of this dis-



GRAND CANYON OF THE COLORADO

The Colorado Plateau with part of the Grand Canyon near the Bright Angel or Cameron Trail. Contour interval 50 feet. (From Bright Angel Quadrangle, United States Geological Survey.)

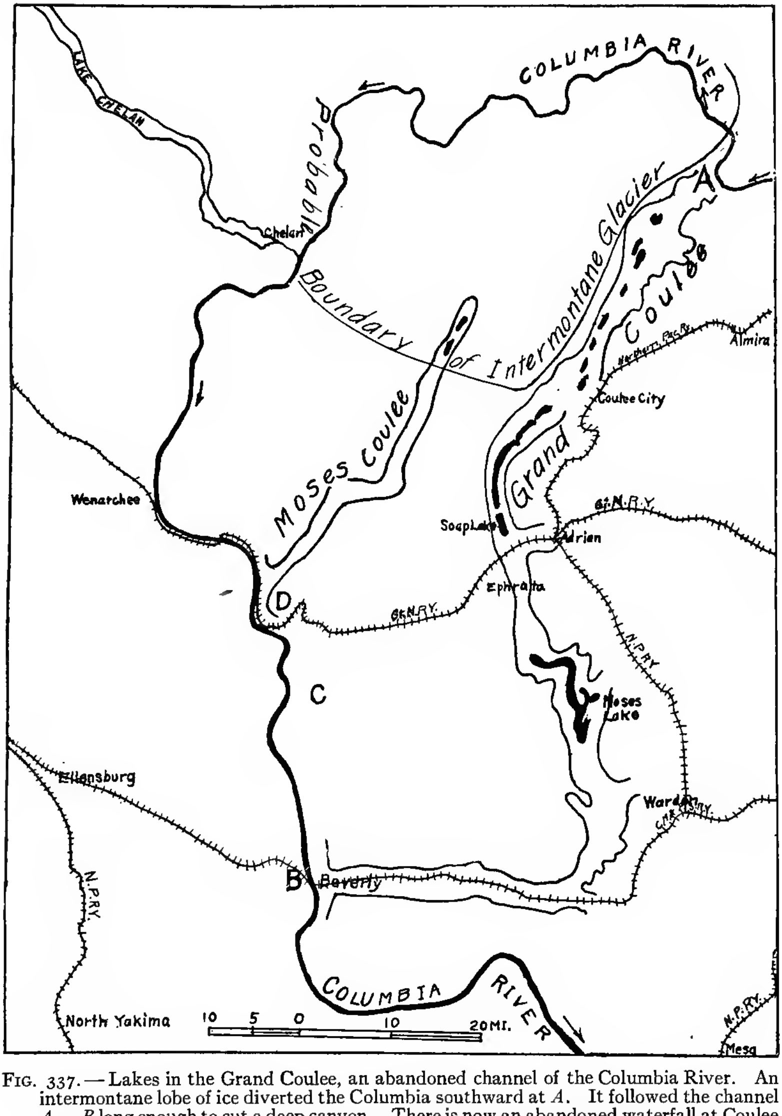


FIG. 337.—Lakes in the Grand Coulee, an abandoned channel of the Columbia River. An intermontane lobe of ice diverted the Columbia southward at *A*. It followed the channel *A* — *B* long enough to cut a deep canyon. There is now an abandoned waterfall at Coulee City, and another (Fig. 69) at *C*. Moses Coulee seems to have been eroded entirely by glacial waters.

tance it flows between steeply rising canyon walls, the grandest portion of which is the so-called Grand Canyon, which is over 200 miles in length. Here the walls in places rise 6000 feet above the river, and with such precipitousness that descent into the canyon is, in most places, impossible. No large streams join the Colorado in its canyon area, though there are numerous tributary canyons through which water sometimes flows.

The canyon form varies from one part of the course to another, according to the nature of the enclosing rock, in some parts where the rock is fairly uniform being narrow and precipitous, in others, where the strata are more variable, flaring toward the top and being bordered by a series of rock terraces. In one place the canyon widens so that the distance across at the top is 10 miles or more. Throughout most of its course the canyon is cut in nearly horizontal sedimentary strata, but in parts of the Grand Canyon the river has cut down to a worn-down, buried, mountain area, in the highly folded and complex strata of which the bottom of the canyon is sunk. The river is here superimposed upon the mountain structure that is hidden from view beneath thousands of feet of sedimentary strata.

The Colorado Plateau is thus bisected by a great gash, forming an impassable barrier to travel across it. Moreover, there are a multitude of minor canyons, for there are a number of large tributary canyons, and, as Powell says, "every river entering these has cut another cañon; every lateral creek has cut a cañon; every brook rises in a cañon; every rill born of a shower, and born again of a shower, and living only during the showers, has cut for itself a cañon; so that the whole upper portion of the basin of the Colorado is traversed by a labyrinth of these deep gorges."

Not only has there been this deep dissection of the plateau by canyons, but the evidence is clear that thousands of feet of strata have been removed from the plateau surface by long-continued denudation, the present canyons, scarps, and table top areas representing a late stage in this long denudation history (Fig. 338).

Impressive as the Colorado Canyon is as a scenic feature, it is even more impressive for the lesson that it gives of the vastness of the changes by which the earth's surface is moulded. The buried mountain area in the canyon bottom tells of a period of deposit in the sea, followed by one of folding and then by long subaërial denudation by which the mountains were worn to a condition of low relief. Then comes submergence and the deposit of thousands of feet of sedimentary strata, completely covering the peneplained mountain area. Following this was uplift and a long, complex denudation history, with accompanying faulting, minor folding, and volcanic activity. During this denudation thousands of feet of strata have been removed, and the plateau has been traversed by a series of canyons, one part trenching the strata to a depth of over a mile. Such a history, which is only fragmentary, testifies eloquently to the vast duration of geological time and the complexity of the processes by which the topography of to-day has been evolved.

Plains of the Great Basin. — Between the low, short, mountain ranges of the Great Basin (Fig. 339) are depressions of various origins into which streams and wind have carried sediment, which, strewn over the valley

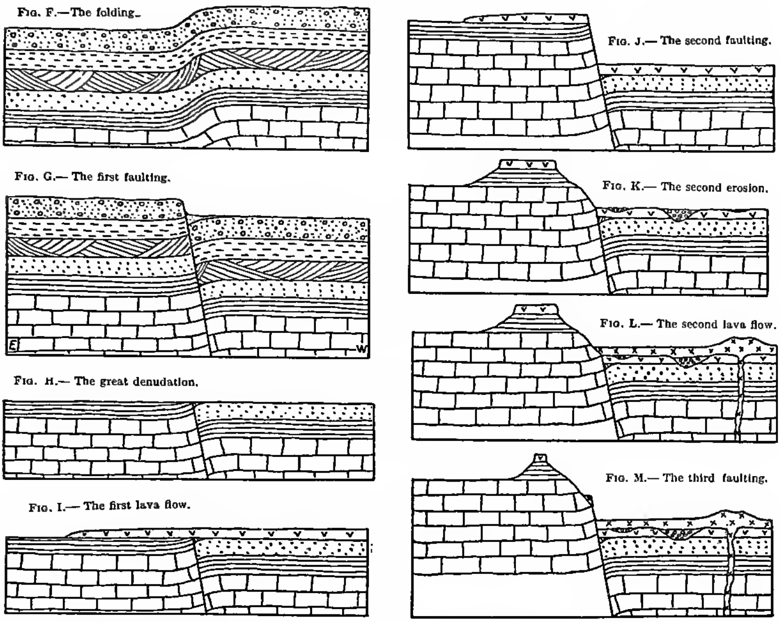


FIG. 338. — Eight stages in the complex history of folding, faulting, denudation, emission of lava, canyon cutting, etc., by which the Colorado Plateau has reached its present form. (D. W. Johnson.)

bottoms, has formed deposits varying in extent and degree of regularity. In some cases plains of considerable size have been formed, and in others the gentle-sloping surfaces of alluvial fans have sufficient levelness to be classified as plains. One of the largest stream deposits is in the very southern portion near the head of the Gulf of California, where the Colorado River has a great, fan-like delta deposit.

In many of the depressions in the Great Basin, lakes have formerly stood, where now only shallow salt lakes, or salinas and alkali flats, exist, as we have already seen was the case near Great Salt Lake. During these stages of higher lakes, the deposits formed lake bottom plains, which now are exposed to the air by evaporation of the waters. Among the most extensive of these lake bottom plains are those around the Great Salt Lake, but there are many other similar plains in the Great Basin.

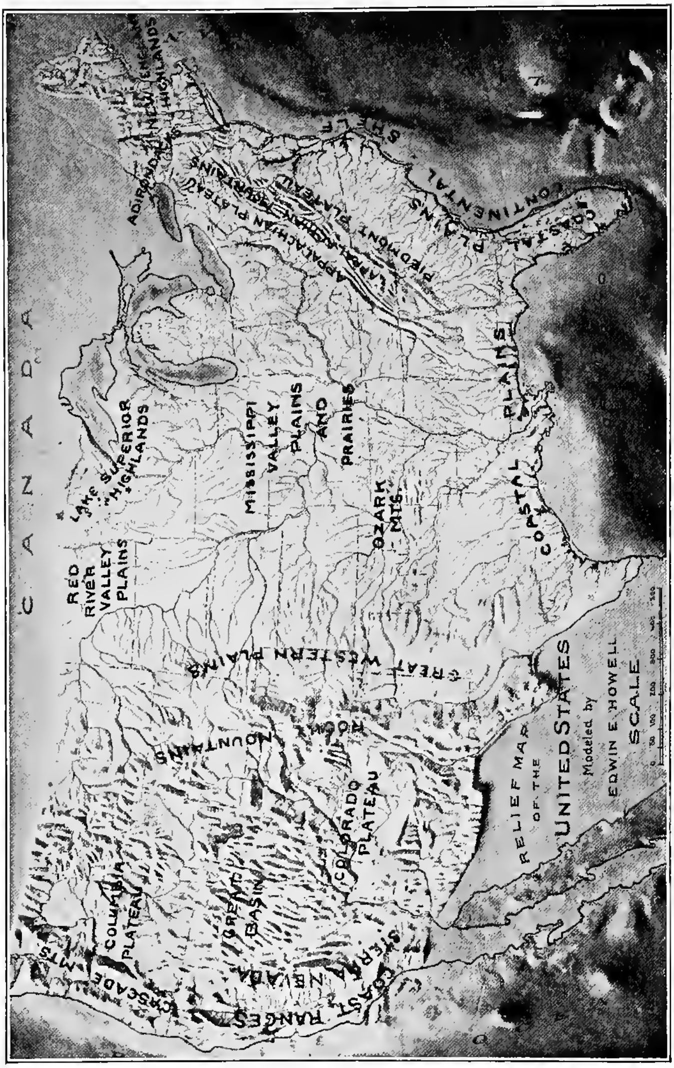


FIG. 339. — Model of the United States, showing the physiographic provinces and including the location of the several plains and plateaus.

Where not saline or alkaline, these level surfaces are well adapted to agriculture if water can be brought for irrigation. This can be done especially well on the alluvial fans, and on the plains near the mountains from which streams issue, and such spots form oases in the general desert, as near Salt Lake City.

The Great Valley of California. — The broad valley between the Coast Ranges and Sierra Nevada is essentially a plain, sloping upward toward each mountain base, with the largest slope toward the Sierra. This plain undulates in a longitudinal direction because it consists of a series of coalescing alluvial fans, which develop strength of form near the mountains; but toward the valley axis the alluvial fan character becomes more indistinct. The moderate slope of the surface and the fertile soil give to this broad plain great agricultural possibilities, which are realized in the north where there is sufficient rainfall, and in the arid southern part wherever water can be obtained from the alluvial-fan-building streams for use in irrigation. The Willamette valley in Oregon and the Puget Sound lowland in Washington are smaller basins, between the Cascades and Coast Ranges, but with less alluvial filling than in the valley of California.

The Pacific Coast. — No broad coastal plain borders the Pacific coast; but, for most of the distance, mountains rise from the coast line. Here and there, however, there are narrow strips of coastal plain, uplifted above the sea and fringing the mountain base. At stream mouths, too, there are delta deposits of small extent. On such a coast there is small chance for settlement, communication with the interior is interfered with by the mountains, and travel along the coast is difficult. It reminds one of the coast of Italy, where the railways from the coast, as at Genoa, must at once tunnel into the mountains, while those along the coast pass through a succession of tunnels. Coming out of one tunnel and revealing a vista of the sea, and of a narrow delta plain occupied by a village, the train almost at once tunnels into the next spur, and so on for miles. On the Pacific shore, coastwise railways have not yet been built, except in part of the distance between San Francisco and Los Angeles, nor is travel by road possible along most of the coast. It offers a striking contrast to the low, flat, coastal plains of the Atlantic coast, over which roads and railways can be built anywhere, excepting where swamp lands interfere.

References to Literature

C. Abbe, Jr. Physiography of Maryland, Md. Weather Service, Vol. 1, 1899, 35 pp.

H. H. Barrows. Geography of the Middle Illinois Valley, Bull. 15, Ill. Geol. Survey, 1910, 128 pp.

Isaiah Bowman. Physiography of the United States, Forest Physiography, New York, 1911: Atlantic and Gulf Coastal Plain, pp. 498–553; Appalachian Plateaus, pp. 685–720; Prairie Plains, pp. 460–497; Great Plains, pp. 405–459; Columbia Plateaus, pp. 192–206; Colorado Plateaus, pp. 256–299; Arizona Highlands, pp. 246–255; Lower Colorado Basin, pp. 236–245; Great Basin, pp. 210–235; Pacific Coast Valleys, pp. 177–191.

M. R. Campbell and A. C. Mendenhall. Geologic Section along the New and Kanawha Rivers in West Virginia, 17th Ann. Rept., U. S. Geol. Survey, Part 2, 1896, pp. 473–511.

W. B. Clark and E. B. Matthews. The Physical Features of Maryland, Md. Geol. Survey, Vol. 6, 1906, pp. 26–259.

Collier Cobb. North Carolina, Journ. School Geog., Vol. 1, 1897, pp. 257–266, 300–308.

G. E. Condra. Geography of Nebraska, Lincoln, 1906, 192 pp.

N. H. Darton. Geology and Water Resources of Nebraska West of the One Hundred and Third Meridian, 19th Ann. Rept., U. S. Geol. Survey, Part 4, 1898, pp. 719–785; Underground Waters of a Portion of Southeastern Nebraska, Water Supply Paper 12, U. S. Geol. Survey, 1898.

W. M. Davis. The United States of America, Mill's International Geography, 1899, pp. 710–773; The Drainage of Cuestas, Proc. Geol. Assoc., Vol. 16, 1899, pp. 75–93; The Development of Certain English Rivers, Geog. Journ., Vol. 5, 1895, pp. 127–146; Küstenebenen, Ebenen, und Hochebenen, Erklärende Beschreibung der Landformen, Leipzig, 1912, pp. 197–245; Excursion to the Grand Canyon of the Colorado, Bull. Mus. Comp. Zoöl., Vol. 38, 1901, pp. 107–201; Excursion to the Plateau Province of Utah and Arizona, *ibid.*, Vol. 42, 1903, pp. 1–50.

E. A. Dietz. The Fall Line, Journ. Geog., Vol. 4, 1905, pp. 244–248.

J. S. Diller. A Geological Reconnaissance in Northwestern Oregon, 17th Ann. Rept., U. S. Geol. Survey, Part 1, 1896, pp. 441–520.

C. R. Dryer. Studies in Indiana Geography, Terre Haute, 1897, 113 pp.

C. E. Dutton. Geology of the High Plateaus of Utah, Powell's U. S. Geog. and Geol. Survey, 1880, 307 pp.; Tertiary History of the Grand Cañon District, Monograph 2, U. S. Geol. Survey, 1882, 264 pp. and atlas.

F. V. Emerson. Geography of Missouri, Bull. Univ. Missouri, Educational Series, Vol. 1, 1912, 74 pp.

N. M. Fenneman. Physiography of the St. Louis Area, Ill. Geol. Survey, Bull. 12, 1909, 83 pp.

Henry Gannett. The United States, Stanford's Compendium of Geography and Travel, North America, Vol. 2, London, 1898.

L. C. Glenn. South Carolina, Journ. School Geog., Vol. 2, 1898, pp. 9–15, 85–92.

H. E. Gregory. Physiography of the United States, Physical and Commercial Geography, Boston, 1910, pp. 58–65.

Arnold Guyot. Physical Structure and Hypsometry of the Catskill Mountain Region, Amer. Journ. Sci., 3d series, Vol. 19, 1880, pp. 429–451.

C. W. Hall. The Geography and Geology of Minnesota, Minneapolis, 1903, 299 pp.

A. Hague and S. F. Emmons. Great Basin, King's Report of the Geological Exploration of the Fortieth Parallel, Prof. Papers of the Engineering Dept. U. S. Army, Vol. 2, Descriptive Geology, 1877, pp. 311–890.

A. Heilprin. The Catskill Mountains, Bull. Amer. Geog. Soc., Vol. 39, 1907, pp. 193–201.

R. T. Hill. The Geography and Geology of the Black and Grand Prairies, Texas, 21st Ann. Rept., U. S. Geol. Survey, Part 7, 1901, pp. 1–666; Physical Geography of the Texas Region, Folio 3, Topographic Atlas of the United States, U. S. Geol. Survey, 1900.

F. M. Hodge. The Enchanted Mesa, Nat. Geog. Mag., Vol. 8, 1897, pp. 273–284.

W. D. Johnson. The High Plains and their Utilization, 21st Ann. Rept., U. S. Geol. Survey, Part 4, 1900, pp. 601–741; *ibid.*, 22d Ann. Rept., Part 4, 1902, pp. 631–669.

J. F. Kemp. Ore Deposits of United States and Canada, Eng. and Min. Journ., New York, 1893.

L. Lesquereux. On the Origin and Formation of the Prairies, Worthen's Geol. Survey of Illinois, Vol. 1, 1866, pp. 238–254.
W J McGee. The Geology of the Head of Chesapeake Bay, 7th Ann. Rept., U. S. Geol. Survey, 1888, pp. 537–646; The Lafayette Formation, *ibid.*, 12th Ann. Rept. 1891, pp. 347–521.
H. J. Mackinder. Britain and the British Seas, New York, 1902, 377 pp.
C. F. Marbut. Physical Features of Missouri, Mo. Geol. Survey, Vol. 10, 1896, pp. 11–109.
Lawrence Martin. The Physical Geography of Wisconsin, Bull. Wis. Geol. Survey (in press).
G. C. Matson and F. G. Clapp. Geology of Florida, 2d Ann. Rept., Florida Geol. Survey, 1908–1909, pp. 25–49; **G. C. Matson and S. Sanford,** Water Supply Paper 319, U. S. Geol. Survey, 1913, 445 pp.
H. R. Mill and Others. International Geography, New York, 1899.
J. W. Powell. Exploration of the Colorado River of the West, Washington, 1875, 291 pp.; Physiographic Regions of the United States, National Geographic Monographs, New York, 1896, pp. 65–100.
H. Reusch. The Norwegian Coast Plain, Journ. Geol., Vol. 2, 1894, pp. 347–349.
H. Ries. Economic Geology of United States, New York, 1907, 451 pp.
I. C. Russell. North America, New York, 1904, 435 pp.
R. D. Salisbury. The Physical Geography of New Jersey, N. J. Geol. Survey, Vol. 4, 1898, 200 pp.
S. Sanford. The Topography and Geology of Southern Florida, 2d Ann. Rept., Florida Geol. Survey, 1908–1909, pp. 177–231.
N. S. Shaler. United States of America, New York, 1894.
G. B. Shattuck. Coastal Plain, Pliocene and Pleistocene, Md. Geol. Survey, 1906, 137 pp.
E. A. Smith. Report on the Geology of the Coastal Plain of Alabama, Geol. Survey of Alabama, 1894, 759 pp.
J. R. Smith. Plateaus in Tropical America, 8th International Geographical Congress, Washington, 1905, pp. 829–835.
J. E. Spurr. Descriptive Geology of Nevada South of the Fortieth Parallel, Bull. 208, U. S. Geol. Survey, 1903, 229 pp.
R. S. Tarr. Physical Geography of New York State, New York, 1902, Chapter I, Physiographic Features; Chapter III, Plains and Plateaus; Chapter XII, Influence of Physiographic Features upon Industrial Development; Economic Geology of United States, New York, 4th edition, 1903.
W. S. Tower. Plateau Province, Regional and Economic Geography of Pennsylvania, Bull. Geog. Soc. Phila., Vol. 4, 1906, pp. 204–217, 271–281.
A. C. Veatch. Long Island, Prof. Paper 44, U. S. Geol. Survey, 1906, pp. 28–32; Louisiana-Arkansas, *ibid.*, Prof. Paper 46, 1906, pp. 14–69.
O. D. von Engeln. Effects of Continental Glaciation on Agriculture, Bull. Amer. Geog. Soc., Vol. 46, 1914, pp. 241–264, 336–355.
R. H. Whitbeck. Economic Aspects of Glaciation in Wisconsin, Annals Assoc. Amer. Geographers, Vol. 3, 1913.
D. E. Willard. The Story of the Prairies, Chicago, 1907, 377 pp.

TOPOGRAPHIC MAPS

Buttes

Coleman, Tex.	Mt. Carrizo, Colo.	Bisuka, Idaho

Central Plains

Madison, Wis.	Marion, Iowa	Butler, Mo.
Jefferson City, Mo.	Lacon, Ill.	Ottawa, Ill.

Coastal Plain

Winterville, N.C.	Leonardtown, Md.	Pt. Lookout, Md.
Atlantic City, N.J.	Barnegat, N.J.	Norfolk Special

Dissected Arid Plateau

Higbee, Colo.	Kaibab, Ariz.	Mt. Taylor, N.M.

Dissected Humid Plateaus

Marshall, Ark.	Centre Pt., W.Va.	Pikeville Special, Tenn.
Skaneateles, N.Y.	Ovid, N.Y.	Kaaterskill, N.Y.

Escarpments

Hollow Springs, Tenn.	Niagara Gorge, N.Y.	Fond du Lac, Wis.

Great Plains

Wichita, Kans.	Lamar, Colo.	Coleman, Tex.
Great Falls, Mont.	Palo Pinto, Tex.	Denver and Vicinity, Colo.
Lexington, Neb.	Syracuse, Kan.	Kearney, Neb.

Lake Plains

Lassen Peak, Cal.	Sierraville, Cal.	Disaster, Nev.
Fargo, N.D.	Toole Valley, Utah	Salt Lake, Utah
Niagara Gorge, N.Y.	Hamlin, N.Y.	Rochester Special, N.Y.

Lava Plains

Boise, Idaho	Modoc Lava Bed, Cal.	Mt. Taylor, N.M.

Mesas

Brownwood, Tex.	Higbee, Colo.	Kaibab, Ariz.
Watrous, N.M.	Mt. Taylor, N.M.	The Dells, Wis.

CHAPTER XV

MOUNTAINS

THE TERM *MOUNTAIN*

Mountains, Hills, and Plateaus. — In common usage the term *mountain* applies to any unusual elevation (Fig. 340). Thus on the Texas plains, a butte 200 feet high may be called a mountain; the dissected Allegheny Plateau, where it rises above the Hudson valley, is

FIG. 340. — The Alps in Austria, rising above the snow line.

known as the Catskill Mountains, and the escarpment bordering this plateau on the north is known as Helderberg Mountain. On the other hand, an integral part of the Appalachian Mountain system is commonly called the Berkshire Hills, and another, lower part, the Piedmont Plateau.

Folded Structures in Mountains. — In this book the term *mountain* is used in a more restricted sense, referring to those parts of the earth's crust which have been so disturbed by diastrophic movement as to notably influence the topographic forms, either directly by uplift or indirectly by denudation working upon the disturbed strata. In the plain or plateau the strata are essentially horizontal, even though higher than many mountains; in the mountain the strata diverge from the horizontal to an appreciable degree.

A hard-and-fast line cannot be drawn between plateau and mountain, for there is every gradation from horizontal to inclined strata, and plateaus are locally broken by faults, and deformed by folds. Moreover, plateaus may be so dissected as to simulate rugged mountain topography, as in the Catskills, and mountains may be worn to such low relief as to resemble a plain, as in the Piedmont Plateau.

Volcanic Mountains. — Volcanic peaks are not here included under mountains, for they are distinctly the product of vulcanism. Yet they occur among mountains and form noteworthy peaks in mountain chains, and vulcanism in various forms is intimately associated with mountain formation, while volcanic rocks make up a large proportion of many mountain masses.

Here as elsewhere in the study of physiography, gradation of phenomena is found to be the rule. A topical study is not warranted by the phenomena of nature, for everywhere there is intergradation; it finds its only excuse in the demand of simplicity of exposition. Mountains, plains, volcanoes, rivers, and weathering are not phenomena set off by themselves; they are complexly interrelated.

Mountain Types

Relation to Folding and Faulting. — The disturbance of strata, forming mountains, may be brought about either (1) by folding, (2) by faulting, or (3) by combined folding and faulting; and either the folding or the faulting may be very simple or very complex. The strata involved may be sedimentary, igneous, or metamorphic, or a combination of these. The disturbance may take place with or without visible igneous activity, though it is probable that subterranean intrusion occurs in connection with most extensive mountain formation.

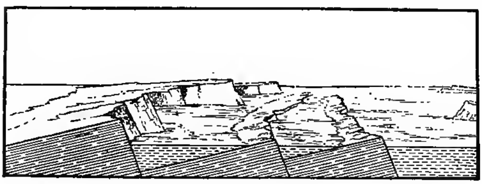


FIG. 341. — Fault block mountains.

Fault Block Mountains.—A simple type of mountain results from the tilting of strata on one side of a fault plane, forming the *fault block mountain.* In this case a ridge is formed, with an escarpment face on the side toward the fault, and a gentle slope in the opposite direction, the inclination of this slope depending on the dip of the inclined strata (Fig. 341). This type of mountain is found in the Great Basin region of southern Oregon, and many of the ridges in the Great Basin farther south have been assigned to the same cause. Some of the Basin Ranges of Oregon are 10 to 40 miles long and over 1000 feet high. Similar faulted blocks are often developed in plateau uplift, and often the inclination of the strata is very slight, so that there is every gradation from the broken, tilted fault block to the broken, untilted blocks, both faced by escarpments. At times the faults merge into monoclinal folds, and thus there is gradation from tilted fault blocks to escarpments due to folding. Ridges due to monocline folding are common in the plateau region of Utah and Wyoming.

Between the fault block ranges sinking may take place; and either this movement or continued uplift of the fault blocks is still in progress.

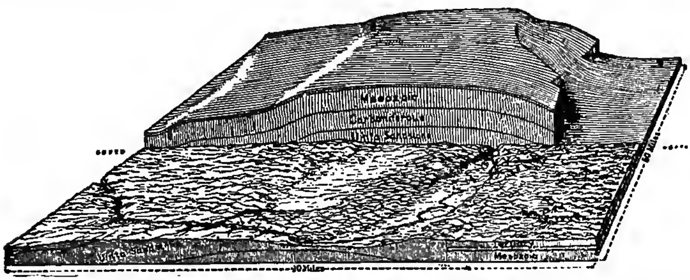


FIG. 342. — Block diagram of the Uinta Mountains, with original mountain arch in the background and the present erosion forms in the foreground. (Powell.)

This is proved by the faulting of alluvial fan deposits and the prevalence of earthquakes, showing the recency of origin of the Basin Ranges.

The Arched Mountain Type. — A second mountain type of simple form is that caused by the updoming of a surface with little or no faulting, and with no complex folding, — merely a gentle dip of the strata from the centre of the domed area. When dissected, such a dome may develop the rugged topography of mountains. The Black Hills are of the *arched mountain type*. The mountain dome is about 50 by 100 miles, and now rises to a height of between two and three thousand feet. It is surrounded by concentric ridges and valleys, related to resistant and weak strata. Before it was unroofed, this dome must have risen at least 6000 feet above the adjacent plains.

Simple arching may rear the strata much higher and give rise to more pronounced mountain topography. Powell named such a mountain form the *Uinta type*, after the Uinta Mountains of Wyoming and Utah, where he found it developed. This mountain range is a broad, flat arch, fully 150 miles long and 50 miles broad, rising 10,000 to 11,000 feet above sea level and 5000 to 6000 feet above the surrounding plateau. The strata are nearly horizontal along the crest, but dip steeply at the margins and then quickly resume their horizontal position (Fig. 342). The present surface has been developed by long-continued denudation, in the course of which, it is estimated, $3\frac{1}{2}$ miles of strata have been removed from the plateau-like crest of the arch.

Laccolitic Mountains. — Roughly circular or elliptical domes may be formed by the intrusion of laccolites beneath strata, raising them so that they dip outward with approximate uniformity from the centre of the dome. This type of mountain was first recognized by Gilbert in the Henry Mountains of Utah, a group of five dome-shaped mountains, the highest of which rises 5000 feet above the surrounding plateau. This type of dome mountain, which may be called *laccolitic mountains*, has since been recognized in other places. Like the Uinta Mountains, these have been greatly denuded and the laccolitic core is revealed (Figs. 324, 343).

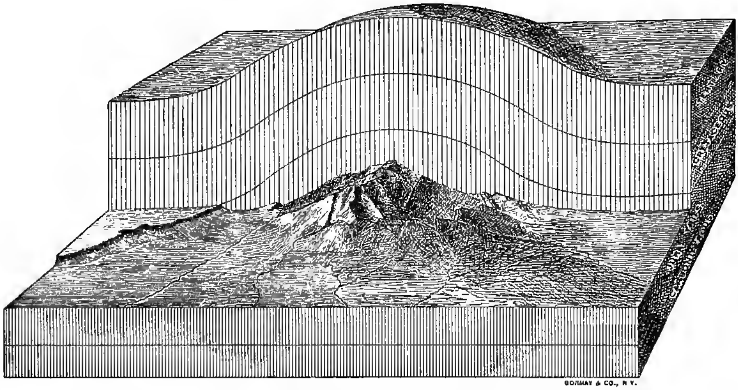


FIG. 343. — Block diagram of the Henry Mountains as they now are, the back of the diagram showing the dome before it was eroded and unroofed. (Gilbert.)

Symmetrical Mountain Folds. — From such simple types of folding there is every gradation to great complexity, and commonly among mountains there is not a single fold, but a number, side by side. In some cases the strata are thrown into a succession of roughly parallel waves, in which the layers dip away from the crest of each wave at fairly uniform angle, and toward the troughs (Fig. 344). Thus a given layer undulates up and down with the regularity and symmetry of the waves of the ocean, each trough or syncline forming a valley, each crest or anticline a ridge. This type of *symmetrical mountain fold* is well illustrated in parts of the Swiss Jura, but, even here, denudation has stripped off some of the folded layers and partly destroyed the symmetry of form, though the undestroyed layers preserve the symmetry of folding. The Appalachian Mountains resemble the Jura in their symmetrical folding, but they are much older and have been so long denuded that the original folds no longer dominate the topography, which is now determined by the relative resistance of the folded strata. The Jura Mountains are the most youthful folded mountains in the world, in stage of the cycle, as the fault blocks of Oregon are probably the most youthful faulted mountains.

Normal Mountains. — In mountain folding the strata are very commonly thrown into far more complex position than in the cases so far considered. There are unsymmetrical folds, with an inclination of the strata greater on one side than on the other; there are closed folds, overturned folds, fan-shaped folds; there are faults of various kinds, inclinations, and degrees of throw; and there is a complex relation of sedimentary, igneous, and metamorphic strata. Among great mountain ranges this is the ordinary condition; so much so that one might call them *normal mountains* (Figs. 345, 346), and the others

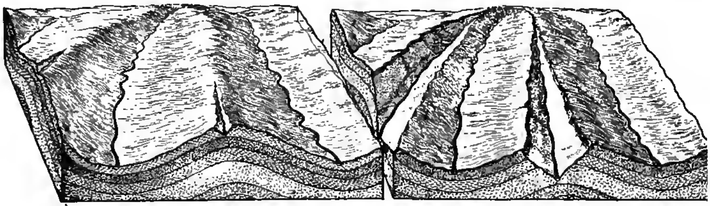


FIG. 344. — Symmetrical mountain folds of the type developed in the Jura, with two stages of erosion.

mere intermediate stages between the plain and the mountain. It would doubtless be possible to classify mountains of this complex character, but the attempt does not seem profitable, for there is almost infinite variety in the complexity. This class of mountain might be called the Alpine, or Himalayan, or Andean, or Rocky Mountain type, if a name were needed.

Distribution of Mountains

The Two Great Mountain Belts. — Most of the really lofty mountains of the world, and the ones in which the evidence of present growth is most noticeable, are arranged in two great belts, the one nearly surrounding the Pacific, the other along an east-west circle north of the equator (Fig. 347). These are the belts already noted (pp. 417 and 478) as the earthquake and volcanic belts — both phenomena associated with growing mountains. It is further noteworthy that the lofty mountains of these belts are mainly marginal to the continents, though some rise off the continent edge or island chains, and some back from the continent edge, as in southern central Asia, and in western United States. Plateaus are commonly associated with these mountain

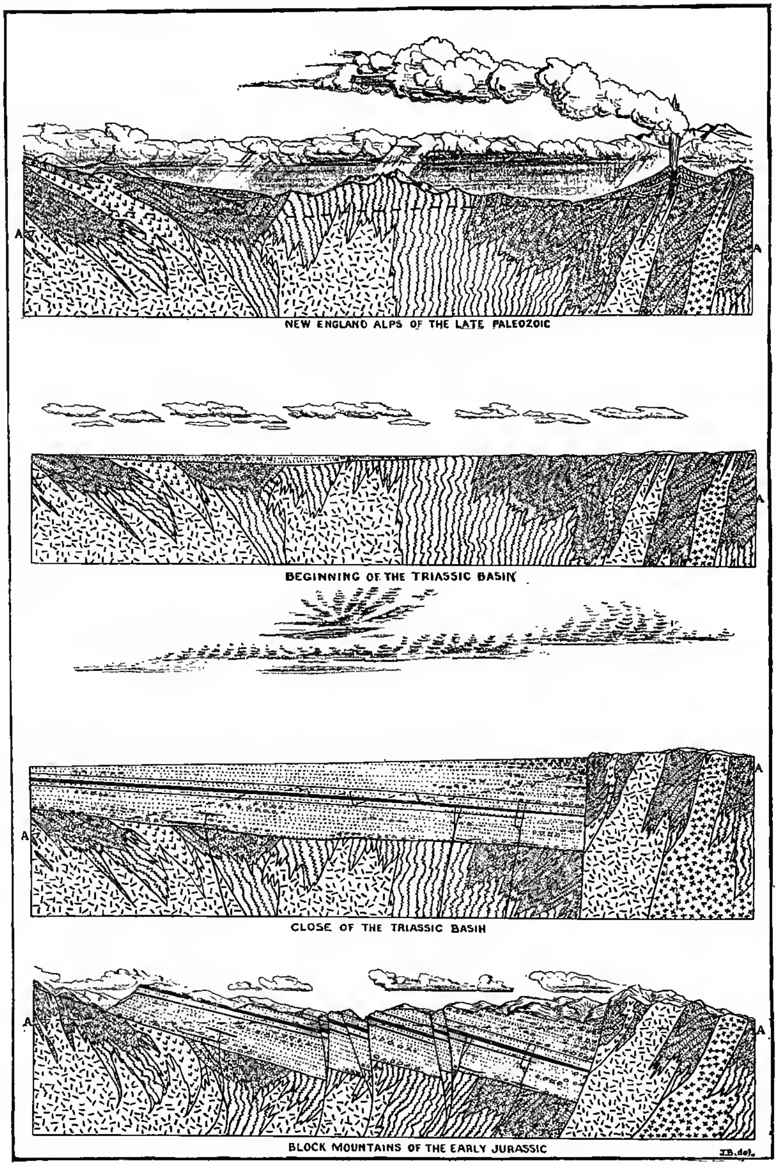


FIG. 345. — Normal mountains in central Connecticut.

Four stages in the development of a mountainous region. Still earlier stages of folding, faulting, vulcanism, and denudation preceded the first shown here, for which more precise data as to the topography of the Paleozoic and pre-Paleozoic are lacking. (Barrell, Geol. Survey of Connecticut.)

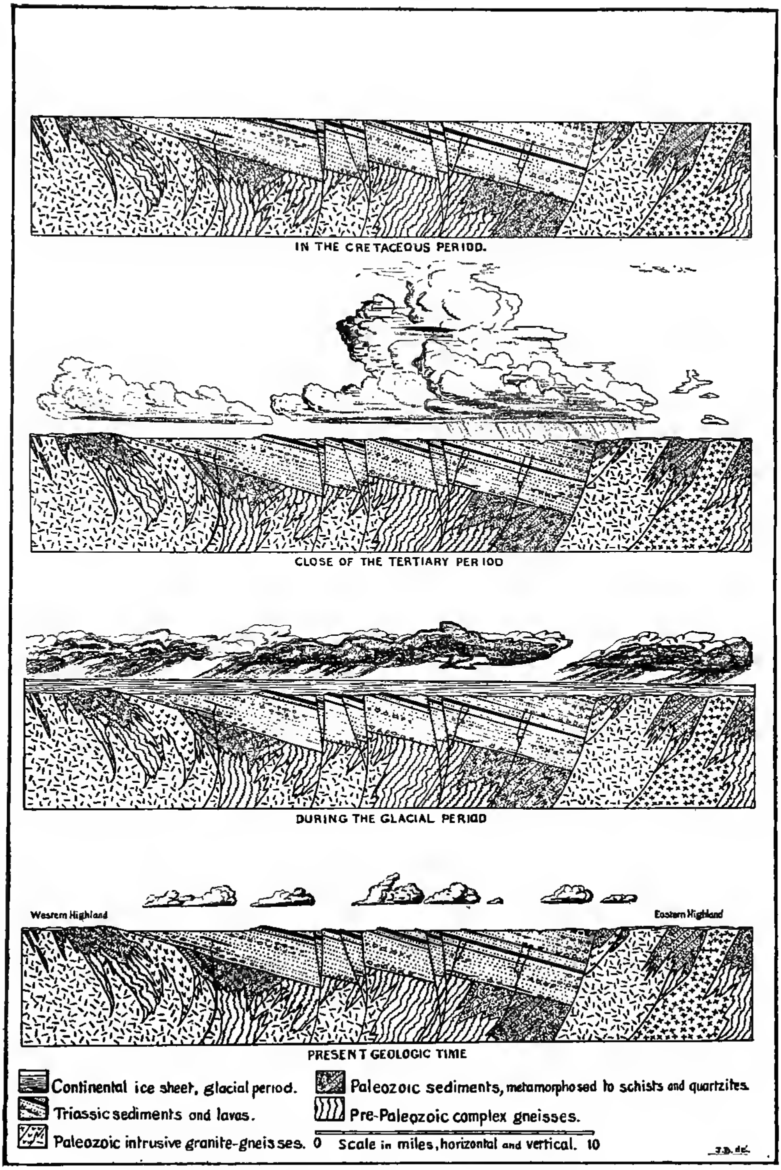


FIG. 346. — Normal mountains in central Connecticut.

Four additional stages in the history of diastrophism and erosion in southern New England. The clouds suggest climatic conditions and furnish a rough vertical scale, the cumulus clouds being about a mile above the earth's surface. (Barrell, Geol. Survey of Connecticut.)

uplifts, and very often the plateaus occupy more area than the folded mountain uplifts.

Besides these two mountain belts there are individual chains here and there, both on the land and in the sea. Of the former the mountains of western Africa are an instance; and in the Pacific and Indian oceans are many chains rising from the sea floor. These are all mountains of recent or present growth, but there are many chains which rose in a former time and have since been exposed to denudation, with little or no regrowth. Such mountains, which are not in the two belts of recently elevated chains, have often been so worn down that they are no longer classed among the lofty mountains of

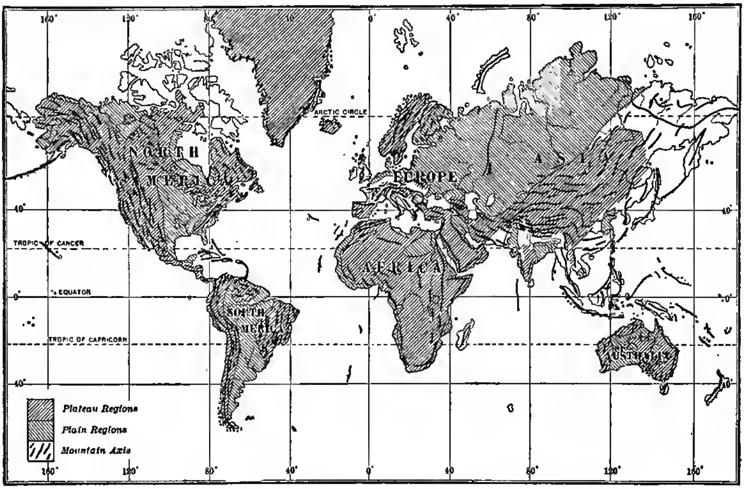


FIG. 347. — Distribution of present-day mountains in the world.

the world; and some are reduced to such low relief that they do not commonly pass for mountains. Among the ancient mountains, now greatly reduced, may be mentioned the Appalachians of eastern United States, the Brazilian Highlands, a large part of the British Isles, the Scandinavian Peninsula, and parts of Germany and France.

Mountain Folding of Various Dates. — Many mountains have been subjected not merely to one period of uplift and folding, but have suffered disturbance again and again. The Appalachian Mountains, the Rocky Mountains, and the Alps have had such complex history, but the Appalachians were subjected to their latest period of folding in long past geological time, while the Alps and Rocky Mountains have suffered recent regrowth (Fig. 348). Thus it is evident that a line along which folding has once taken place may be the seat of subsequent disturbance; or the later foldings may not affect these regions but occur along entirely new lines near by, or remote from them, as the case may be.

The denudation of mountains and plateaus supplies great quantities of sediment for removal to lower levels, and the repeated uplifts tend to continue the supply. Because of these facts mountains have been called the backbones of continents, connected by a tissue of sediment supplied by their denudation. Out of the detritus thus furnished have been built many of the plains that stretch between the mountains; and even a large portion of the strata in the mountains have been derived in similar manner, and later folded to form parts of mountains. The regularly folded Appalachians, for example,

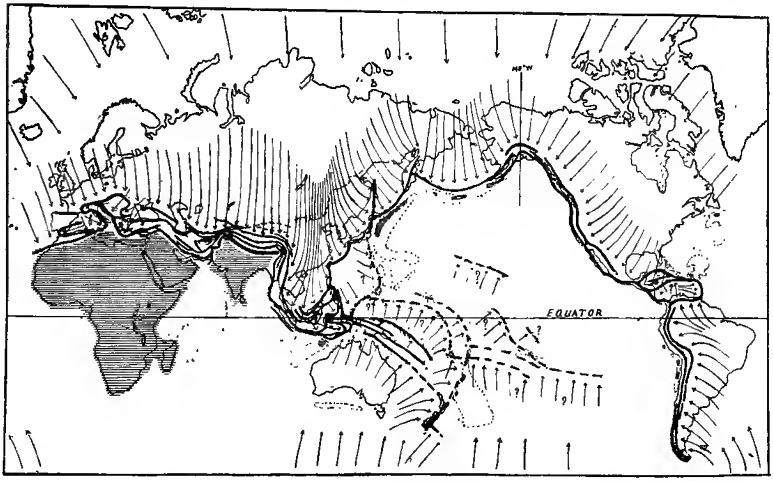


Fig. 348. — Map of the world to show the distribution of mountains of Tertiary age The arrows show supposed directions of crustal movement in the mountain making. (Taylor.)

are composed of sedimentary strata, first deposited in the sea at the western base of the older Appalachians of the Piedmont Plateau, from which the sediment came, and then folded into mountain form.

Some of the important facts regarding the mountains of the world are summarized in the following table, in which the elevations of a few of the higher plateaus are added for comparison.

	Feet
Abyssinian Plateau	6–9,000
Aconcagua, Andes, Argentina (highest in South America)	22,860
Apo, Mindanao, Philippines	10,312
Ararat, Turkey in Asia	17,325
Mt. Blanc, France (highest in Alps)	15,781
Bolivian Plateau	10–13,000
Brazilian Plateau	2–3,500
Chimborazo, Andes, Ecuador	20,498
Cotopaxi, Andes, Ecuador	19,613
Elbruz, Caucasus, Russia	18,200
Erebus, Antarctica	12,365
Etna, Sicily	10,870
Everest, Himalayas, Nepal (highest known in world)	29,002
Fremont Peak, Rocky Mountains, Wyo.	13,790
Fujiyama, Japan	12,365
Hekla, Iceland	5,110
Kenia, Africa	19,199
Kilimanjaro (highest known in Africa)	19,717

	Feet
Kosciusko, Australia (highest in Australia)	7,336
Kunchinjunga, Himalayas	28,156
Logan, St. Elias Range (highest in Canada)	19,539
McKinley, Alaska (highest in North America)	20,464
Marcy, Adirondacks, New York	5,344
Matterhorn, Alps	14,780
Mauna Kea, Hawaiian Islands	13,805
Mauna Loa, Hawaiian Islands	13,675
Mayon, Luzon Island, Philippines	8,900
Mexican Plateau	5–6,000
Mitchell, Appalachian Mts., N. C. (highest in eastern United States)	6,711
Orizaba, Mexico (highest in Mexico)	18,314
Pico del Turquino, Cuba	8,600
Pike's Peak, Rocky Mountains, Colorado	14,111
Popocatepetl, Mexico	17,798
Rainier, Cascade Mountains, Washington	14,408
Ruwenzori, Africa	16,815
St. Elias, Alaska	18,025
San Francisco Mountain, Arizona	12,611
Shasta, Cascade Mountains, California	14,380
Tibet Plateau	10–15,000
Tina, Haiti	10,300
Vesuvius, Italy	3,880
Washington, White Mountains, N. H. (highest in northeastern United States)	6,279
Whitney, Sierra Nevada, California (highest in United States)	14,502
Yunque, Porto Rico	3,609

Mountains of Eurasia. — Next to plains, mountains are the most widely distributed and most extensive of land forms. They form a

Fig. 349. — View in the Caucasus with snow-covered slopes and cloud-filled valleys.

large proportion of the area of some continents, notably Asia. Here, in addition to the fringing mountain islands — the Japanese, Philippine, and East Indian Islands, and those of the peninsulas, there is the great complex of mountains in central, eastern, and southern Asia, together forming the greatest mountain area of the earth, and including the highest peak, Mount Everest, 29,000 feet in elevation, towering even above the Plateau of Tibet, which is 15 to 16 thousand feet high. The mountains of southern Asia extend east through the Caucasus (Fig. 349) and Asia Minor, to the Mediterranean region, whose northern shore is mainly bordered by mountains, while mountain spurs project to form the Balkan and Italian peninsulas. The Spanish peninsula includes the Pyrenees and Sierra Nevada ranges in addition to other shorter and lower ones. North of the Alps are the worn-down mountains extending from central France eastward through Germany into Austria and the Balkan Peninsula. The low Urals extend north and south along the eastern boundary of Russia, and an ancient mountain range extends from northern Scandinavia, through the British Isles to Brittany in France. North of Europe is the mountainous Spitzbergen and other Arctic islands. Thus Eurasia has a great number of mountains, extending in all directions, forming a great complex, and in various stages of development, some very old, some even now rising.

Mountains of Africa. — Africa is far less mountainous, for it is mainly a plateau, somewhat broken around the edge; but it is not sufficiently explored for an exact mapping of its mountains. The two principal ranges are the Atlas Mountains in the north, and Cape Mountains in the south. In central eastern Africa some of the peaks, which are volcanic, attain an elevation of nearly 20,000 feet.

Mountains of Australia and Antarctica. — In Australia the principal range is along the east coast, but there are shorter ranges in other parts, none, not even the east coast mountains, being very lofty. New Zealand is part of a mountain range in the sea, and there are scores of others in the Indian and Pacific oceans. The Antarctic continent is too little known to state its condition, though such parts as are explored are mountainous in character.

Mountains in the Americas. — In the New World there is a continuous mountain chain from the southern tip of South America to the northern part, where it spreads apart fan-shaped, one branch going into the Isthmus of Panama, others northeastward through the Caribbean. This Andean system broadens in the centre, especially in Peru and Bolivia, and includes extensive plateaus between the nearly parallel chains. Here is found Aconcagua, the loftiest mountain in the New World, about 23,000 feet, and from the coast the slope goes on down 15,000 feet or more to the deep sea. The Brazilian Highlands are an ancient, worn-down mountain area; and the Venezuela Highlands are another and higher area of the same nature.

North of South America are the West Indian or Antillean Mountains, rising from the sea floor at depths of 16,000 feet or more to elevations of 5000 or 10,000 feet above sea level, forming therefore a really imposing mountain system, though mainly beneath the sea. Short mountain ranges occur in Central America and southern Mexico. Then begins the series of chains of the North American Cordillera, with intermediate valleys and plateaus, which stretch northward to Alaska, and curve westward toward Asia through the Aleutian Island chain. In the United States the ranges of this broad area of north-south mountains are, from east to west, the Rocky Mountains, the Basin Ranges, the Sierra-Nevada-Cascade Ranges, and the Coast Ranges. These mountains attain their culminating height in Alaska, where St. Elias rises 18,025 feet, Logan 19,539 feet, and McKinley 20,464 feet.

The Appalachians of eastern United States and Canada are a worn-down mountain chain, and there is a great area of reduced mountain land in northern and central Canada, besides some low mountain masses in Oklahoma, Texas, and Arkansas. The islands of the Arctic, including Greenland, are mainly reduced mountain land.

All Mountains not Lofty. — From this summarized survey of the mountain areas of the world, from which oceanic mountains have been in the main excluded, it is evident that, in considering the distribution of mountains, attention cannot be confined to those mountains which are lofty. There is, perhaps, as much mountainous area of low relief as is included in the well-recognized mountain chains. Such mountains are old — they have had their period of imposing elevation, but have lost relief under the steady and long-continued attacks of denudation, and have not been notably renewed by recent uplift and folding.

The Growth of Mountains

Mountain Growth not Rapid. — In the chapter on diastrophism it has been shown that mountain growth is in progress in parts of the earth — in the St. Elias Range, the Coast Ranges of California, the Andes, and Japan, for example. This growth is not rapid; it consists of intermittent movements, with long periods of rest, or of such slow movement as to have escaped detection. There is no evidence that mountain growth in the past has proceeded with great rapidity, though, so far as any proof to the contrary goes to show, it may have been more rapid. All that we can be certain of is that, on the whole, the mountain formation has been much more rapid than the levelling processes of denudation, and that, consequently, lofty ranges have been reared.

Cessation of Mountain Growth. — Some areas, where mountains were formed in very early geological ages, have not subsequently been notably disturbed by mountain folding. For example, the peneplained and buried mountain mass in the bottom of the Grand Canyon of the Colorado has not been subjected to refolding in all the ages required to lower it by denudation and in all the subsequent time required for the deposit of thousands of feet of sedimentary strata and for the great denudation since these were uplifted out of the sea. This time is to be reckoned in millions of years, for it spans many geological periods. The Lake Superior-Hudson Bay Highland has had a similar history, and there are many other known cases of areas long ago reared to mountain conditions, and since then immune.

Recurrence of Mountain Growth. — In other cases, as we have seen, there has been recurrent growth, during which the earlier mountains have been much denuded, so that later sediments partly overlap them with notable unconformity. These later sediments are then involved in a subsequent folding, which affects not only them, but the old mountain rocks also. Along certain belts there has been noteworthy recurrence of mountain folding during the geological past; in other places there has been absence of mountain formation during most of geological time, as in the greater part of the area of the Mississippi valley plains.

Uplift in Mountains. — When extensive mountain growth takes place there is, in the first place, definite uplift, often involving a broad area most of which escapes with slight disturbance of the strata, giving rise to plateaus. Here and there in the plateau there may be faulting, or monoclinal folding, or doming or other form of moderate flexure, some parts rising, others sinking; and lava extrusion, either from fissures or from volcanic vents, may take place. But along certain belts there develops notable faulting or folding, or both, and these belts rise as mountain chains of complex structure. From them also lava may outflow, and the wearing down of such mountains by denudation reveals the fact that much igneous rock was intruded beneath them, often in great batholites.

Down Folding in Mountains. — In more or less close association with such mountain uplift, there is commonly, perhaps universally, notable depression. Linear depressions of unusual depth lie close by some of the oceanic mountain chains, for example near Porto Rico and near Guam; deep oceanic water lies off the South American coast; the plain of Lombardy and valley of the river Po lies at the southern base of the Alps; the valley of northern India at the southern base of the Himalaya Mountains; the Great Valley of California between the Coast Ranges and the Sierra Nevada; the Puget Sound-Willamette lowland between the Cascades and the Coast Ranges; and the Death Valley, below sea level, at the eastern base of the Sierra. Within the ranges themselves are smaller basins due to down folding as in the *parks* of the Colorado Rockies. These depressions are often so filled with sediment, washed into them from the mountains, that their true depth is masked. Many deep bays and seas fringing the mountain coasts of the continent are evidently down sunken portions of the crust — the Gulf of Mexico, the Caribbean Sea, the Mediterranean, and the Red Sea, for example. It has already been shown that the Mediterranean is still subsiding along fault planes.

Horizontal Orogenic Movements. — Not only is there great subsidence and notable elevation accompanying mountain growth, or *orogeny;* there are also extensive horizontal movements. It was long ago pointed out that if the strata involved in the folded Appalachians were stretched out to the horizontal position in which they were originally deposited in the sea, they would occupy many miles more area than at present. Evidently, therefore, this part of the earth's crust has been shortened by a shove from one side, which threw the rock layers into folds, as one may fold the leaves of this book by pushing at their margin. In the Appalachians the lateral thrust apparently operated from the Atlantic side. In the Alps, likewise, Heim believes that a lowland 375 to 750 miles wide has been converted by compression and folding into a mountain chain averaging not quite 100 miles in width.

Now recently it has been discovered that rocks are not only folded, and folds overturned by lateral thrust, but great thrust faults are developed, by which slices of the crust are moved bodily over nearly horizontal or gently-inclined planes for many miles (Figs. 350, 351). Many mountains are traversed by such thrust faults, involving a series of horizontal movements and pushing older rocks over later ones. This thrust faulting, clearly shown by the work of Peach and Horn in the ancient mountains of the Scottish Highlands, is a common feature in mountain regions, as in the Front Range of the Rockies in Montana and southern Canada, described by Willis and by McConnell, and in the southern Appalachians. It is of fundamental importance in mountain history. Some of the extremely complex mountain structures of the Alps, originally explained by Heim on the basis of double or fan-shaped folds (Fig. 352), are now thought to be *decken*, or *rock sheets*, determined by horizontal movements of great extent by which older strata have slipped out over younger for distances of many miles. The brilliant work of Bertrand, Lugeon, and others shows this clearly, as is now recognized by Heim (Fig. 352). Following such horizontal movements by (*a*) thrust faulting or (*b*) decken folding, or (*c*) movements upward, as well as forward and back, during two periods of thrust faulting, or (*d*) the folding back of recumbent older layers on younger, it is possible for erosion to form isolated peaks which may be bold in form, because made of resistant older rocks, and give a striking contrast to the mild topography of the weak younger rocks upon which they now rest, as "mountains without roots." Chief Mountain, Montana (Fig. 353), and the group of peaks of the Mythen northeast of Lake Lucerne, Switzerland, are excellent illustrations of such isolated *klippen*, or *drong* mountains.

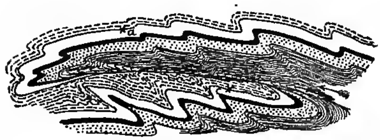


FIG. 350. — Overthrust folding and faulting with minor crumpling. (Heim.)

FIG. 351. — Thrust faulting in the southern Appalachians. (Keith.)

Still a third evidence of horizontal movement is in the plan of mountain chains, best illustrated in the mountains fringing the Asiatic coast. These chains form a series of scallops, or loops, bowed outward (Fig. 348) to a greater or less degree, as in the Himalayas, the Japanese Islands, and the Aleutian Islands. These loops, to which Suess has called attention, have the appearance of a forward gliding of parts of the crust from a polar direction, with accompanying folding and faulting forming mountain ranges. The complex of mountains of eastern and southern Asia would find explanation on the assumption of such an outward movement from this great land mass. It is difficult to explain on any other basis. This point is further considered in later pages (pp. 605–6, 620, 623).

Flowage of Rocks. — In mountains in which denudation has removed the upper layers, the rocks are often found to be not merely bent, but greatly contorted. It is evident that there has been what amounts to flowage of the rocks, though there is no reason for believing that they were melted. Adams has reproduced such flowage in the laboratory, and there can, therefore, be no doubt that rocks, under

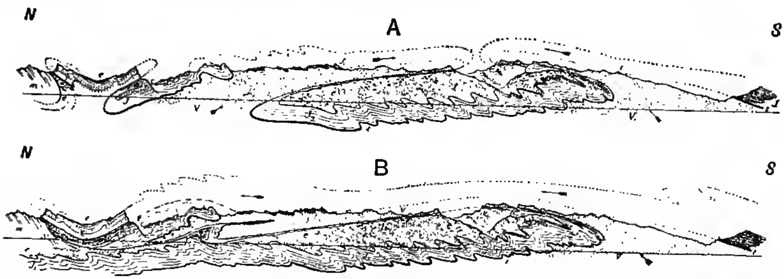


FIG. 352. — *A*. The Glarner double fold, as interpreted by Escher and Heim from 1870 to 1902. *B*. The Glarner rock sheet, as interpreted by Bertrand in 1883, Suess in 1892, and Heim in 1903.

such great pressure as accompanies mountain growth, will flow. Indeed, under great pressure cavities are closed and breaking is impossible, so that the rocks yield to pressures by flowage instead of by breaking. At the surface they yield by breaking. It is probable that faults, visible at the surface and now forming there, are but surface expressions of stresses which, deeper in the earth, are forming folds; and probably mountain folds, now revealed by denudation, were overlain by beds near the former surface in which faulting occurred. Whether rocks under stress will break or bend depends upon (1) the depth and consequently the pressure they are under; (2) the rate at which the stress is applied, a rapidly-applied stress causing breaking, whereas the same stress more slowly applied causes bending; (3) the nature of the rocks, some being far more brittle than others. Probably also other factors have influence, such as temperature and the amount of interstitial water in the rocks.

Names Applied to Mountains

Typical Forms. — Mountains are usually a complex of elevations and depressions, some of the elevations being elongated, others more or less conical, like great hills. The latter are commonly called *mountain peaks*, such as Pike's Peak, or just *mountain*, or *mount*, as Mount St. Elias or Mont Blanc. In the Alps some very sharp peaks are called *needles* (French *aiguille*), and certain pyramidal peaks are known as *horns* — the Matterhorn, for example. Others more dome-shaped are sometimes called *domes*. The elongated elevations are known as *ridges*, and these are sometimes very long and narrow, and often steeper on one side than on the other. Ridges are well developed in the Jura and in the Appalachian Mountains. Both ridges and peaks

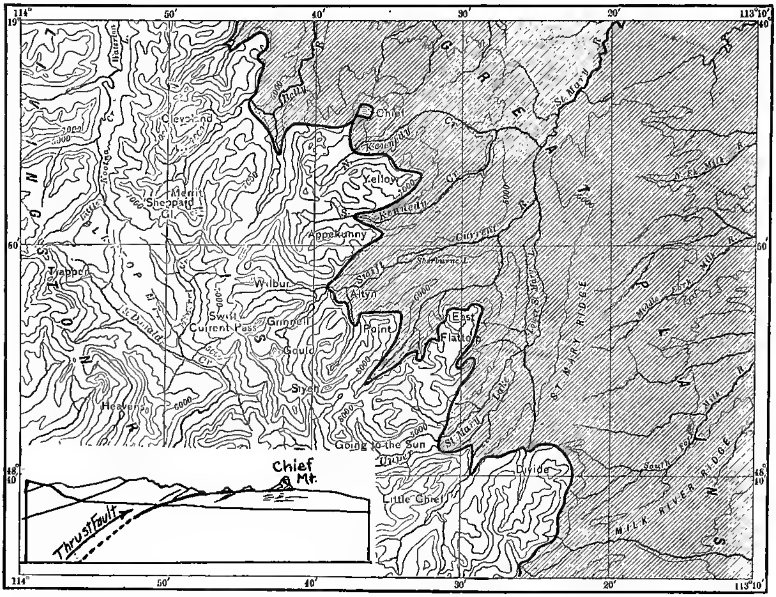


FIG. 353. — The overthrust to the east in the Front Range of the Rocky Mountains in Glacier National Park, with the Algonkian and Paleozoic (white) on top of the Cretaceous (oblique lines). Chief Mountain is a klippen, or drong mountain. (Willis.)

are commonly products of denudation, acting upon the inclined mountain rocks. There are many valleys of erosion, some broad and U-shaped, as where broadened and deepened by glacial erosion, others narrow stream gorges. The longitudinal valleys extend parallel to the ridges, while the transverse streams cross the ridges by water gaps, which are one form of *mountain pass* (Fig. 371). Wind gaps, however, are also passes, and in general any depression in mountains across which travel is possible, is a pass. Passes are often valleys caused by erosion, but not necessarily so.

Ranges, Systems, and Cordilleras. — A group of mountain forms, usually including numerous peaks or ridges with intervening valleys, is known as a *mountain range*. The terms *mountain system* and *mountain chain* are often employed as synonymous with range, though it is more common to use these terms to mean something more extensive than range. For example, the Rocky Mountains consist of a number of ranges, such as the Front Range, the Big Horn Mountains, etc., together making the Rocky Mountain System. But there is much confusion in the common usage of these terms. A group of mountain systems may be called a *cordillera*; for example, the Cordillera of western United States, which includes the Rocky Mountain System, the Basin Ranges, the Sierra Nevada-Cascade System, and the Coast Range System.

Fig. 354. — The Himalayas, loftiest mountains in the world.

Ranges, systems, and chains are constructional forms, due to uplift of those portions of the crust, or to down sinking of the areas on one or both sides, or to both of these movements combined. Such change of level usually affects linear portions of the surface and, therefore, these forms are commonly elongated. There are often long valleys between them, such for example as the Great Valley of California, between the Sierra Nevada and the Coast Ranges, and the Swiss Plateau or Alpine Foreland between the Alps and the Jura. The plateau and basin area between the Rocky Mountains and the Sierra Nevada-Cascade System is another instance of a depression between mountain chains. Very often such great depressions are basins of interior drainage, because the mountains on one side so cut off the vapour-laden winds that the climate is too arid for the streams to find their way across, and even for the running water to fill the depressions and transform them to lakes. There are areas of such interior drainage in the Andes and north of the Himalayas, as well as in western United States.

Complexity of Mountain Structure

Contrasts with Plains and Plateaus. — With folding and faulting among the primary causes for mountain formation, it follows that the strata will be predominantly inclined, and often inclined at a very high angle, up to the vertical. This fact alone offers a striking contrast to the structure of plains and plateaus (Fig. 355), where the strata are predominantly horizontal, or nearly so. The degree of

Fig. 355. — Folded rocks on the right, as in the Appalachians, grading into horizontal structures on the left, as in the Allegheny Plateau.

complexity of rock position is further increased in many mountains because of the fact of repeated mountain growth, often involving not only the strata of the older mountains, but also later strata, deposited upon them and, by the regrowth, folded or faulted into the ancient mountain mass.

The mountain movements serve to indurate rock strata, and, in places of complex folding, even to alter or metamorphose them, frequently to the extent of completely destroying their original characteristics. Metamorphic and sedimentary strata may, therefore, be side by side and in all positions and relationships. By the movements, too, the rocks are jointed far more than the horizontal strata of plains and plateaus, and the extent of the development of joint planes varies greatly from place to place, thus introducing another element of variation in the nature of the rock and in its power of resistance to denudation.

Finally, igneous rocks are often complexly involved in mountain structure. There frequently are lava flows and ash deposits; there are dikes and sills; and there may be laccolitic intrusions, and even huge batholites of coarsely crystalline granitic rock in the mountain core. These affect the mountain rocks (1) by their own characteristics, (2) by the disturbance of the strata which their intrusion brought about, (3) by metamorphism of the strata near the contact. The igneous rocks, like the sedimentary strata, may be subjected to folding, faulting, jointing, and metamorphic action during the mountain movements.

Ruggedness due to Erosion of Complex Structures. — For these reasons a mountain system is a zone of extraordinary complexity of rock structure and attitude, contrasting absolutely with the simplicity of conditions in plains and plateaus. Sedimentary, metamorphic, and igneous rocks occur in the mountain mass in great variety, with marked difference in degree of resistance to denudation, in all attitudes, and an infinite series of relationships. Naturally, therefore, mountains, when acted upon by denudation, assume a degree of ruggedness and variety of form quite unknown in simpler land forms.

Sculpturing of Mountains

Results of High Altitude. — That the ruggedness for which mountains are noted is not the result merely of elevation is proved by the fact that some plateau areas are higher than mountains which are noted for their ruggedness. It is due primarily to the action of denudation operating upon rocks varying in kind and in altitude. Elevation is, however, a factor in the development of this ruggedness because of (1) original height, (2) original differences in elevation, and (3) the greater scope for the activities of the agents of denudation with elevation.

Fig. 356. — Just above timber line in the Rocky Mountains.

Timber Line. — Peaks and ranges are often high enough to limit the growth of trees (Fig. 356), so there is a *timber line* at an altitude where the mean annual temperature is only 2° or 3° below the freezing point. Gannett has shown that in the United States the altitude of the timber line varies from 4000 feet on Mount Washington in New Hampshire to 12,000 feet in the Colorado Rockies, and from 5500 feet in the

Cascades of Washington to 11,700 feet in the mountains of southern California. In arid regions there is also a lower timber line determined by drought.

High-altitude Weathering. — Mountains are the seat of exceedingly active denudation. Because of their elevation, the temperature is lowered, or the day and night extremes are so great that frost action is vigorous, and exposed rock surfaces are broken by it. Mountain surfaces are often covered with broken rock fragments, where the slope is not too steep for them to remain; while, from the steeper slopes, frost-riven fragments are frequently falling. The abundant steep slopes that develop in mountains, especially in the mountain desert above timber line, give much opportunity for the work of weathering, by keeping the bare rock exposed to the weather. The variable nature of the rocks and the abundant jointing also favour the rapid work of weathering. Probably in no one part of the earth's surface is weathering more active than in lofty mountains. One cannot be among them long without seeing the fall of rock fragments from the cliffs, and, now and then, great masses descending as avalanches (Pl. I).

FIG. 357. — The Royal Gorge of the Arkansas in the Colorado Rockies, a stream-cut canyon half a mile deep.

Stream Erosion. — Lofty mountains are also commonly the seat of heavy precipitation, often in the form of rain or of snow, which, upon melting, gives rise to large volumes of running water. The water entering the rocks aids in weathering by its direct attack through solution or chemical change and by frost action. The streams which run off at the surface have high velocity, because of the steep slope and large volume, and they are also supplied with abundance of cutting tools. Consequently, they readily cut their valleys

FIG. 358.—Cirques, arrêtes, and U-shaped valleys in the mountains of Glacier National Park, Montana. (Chief Mountain Quadrangle, U. S. Geol. Survey.)

in the mountain rock, and, thereby, expose more rock to weathering. Gorges and other steep-walled valleys are common phenomena in lofty mountains; and they may be cut to great depth, because the mountain surface lies high above sea level (Fig. 357).

Glacial Erosion. — The altitude of lofty mountains sometimes results in their rising above snow line, which varies from 18 or 20 thousand feet near the equator to sea level in the polar regions. The snowfall serves as a protecting cover to the mountain on which it lies, though when it descends in avalanches it tears off rock fragments by its friction, and bears them along. Changing to ice, the snow slowly moves down the valleys as glaciers, grinding the valley bottoms and sides. Glacial sculpturing is, as we have seen, a significant factor in the shaping of mountain topography (Pls. V, IX, Fig. 358). In the Alps, for example, a considerable share of the valleys and the sharpened ridges, or *arrêtes*, are due directly or indirectly to ice erosion.

Wind Work. — Wind work is also very important among high mountains. They are exposed to high winds, the winds sweep about in eddies, often concentrated into almost hurricane force, and, wherever bare rock is exposed, loose fragments, even of the size of small pebbles, are driven before them.

Rapidity of Denudation. — Altogether, the denudation of mountains is so favoured that it proceeds with comparative rapidity and with complex results. Elevation gives opportunity for rapid work, and complex rock conditions favour the development of varied form. Consequently high mountains are ordinarily rugged in the extreme, — a maze of peaks and valleys of various forms and sizes. These, though characteristic of such mountains, are not inherent in the mountains, but are developed in the mountain elevation by the processes of denudation.

Forms Sculptured in Mountains

So complex are the forms of mountain sculpture that a complete analysis is here quite out of question. Only a few of the most noteworthy types will be considered.

Ridges. — Where a stratum of resistant rock outcrops, it tends to be left behind in the general wearing down of the surface. If the stratum has a linear outcrop, as is often the case with folded or faulted sedimentary strata, the tendency is for a *ridge* to develop, with a depression or linear valley along the line of the weaker, underlying stratum. The height of the ridge will depend upon the extent to which the differential denudation lowers the surface; its width will vary with the width of the ridge-making stratum; the strength of its development will depend upon the degree of resistance of the ridge-making stratum; and its length will depend upon the extent of the outcrop.

If the strata are vertical, the ridge will have approximately the same slope on the two sides, and ridges will occur parallel to one another at intervals wherever a resistant layer outcrops. If the strata are inclined, as is most common, one side will have an inclination approximately that of the dip of the ridge-making stratum, while the other side will have a steep slope. This is a *monoclinal ridge* or *hogback.*

This form varies with the dip, grading down to the horizontal position of strata, in which a steep face on one side rises to a table top area, a form which characterizes plateau topography.

As denudation proceeds, the removal of the weaker underlying stratum, by sapping, in a manner similar to that observed in plateaus, causes recession of the cliff, and the ridge migrates in the direction of the dip. It also becomes lower at the same time, but will not become lower in relation to the surrounding surface if denudation is freely at work there; indeed, the ridge may even be etched into greater prominence at the same time that it is being lowered and caused to recede. Since ridges, being etched into relief, commonly form divides, there is a migration of divides as the ridge cliff recedes. This process of recession has been called *monoclinal shifting* (Fig. 359).

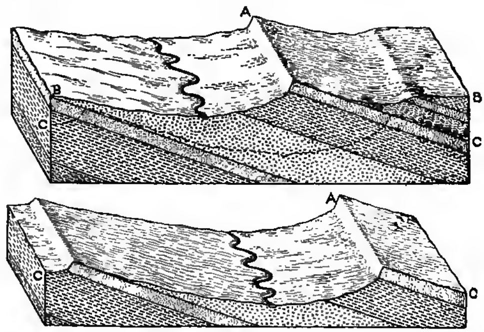


FIG. 359. — While the surface is being worn down from *BB* to *CC*, the monoclinal ridge *A* shifts some distance to the right.

Ridges are naturally most perfectly developed among mountains of sedimentary strata, in which folding or faulting have been of a fair degree of regularity so as to permit linear outcrops, as in the Jura and in the Appalachian Mountains. In the latter, for example, there are ridges many miles in extent, rising to nearly uniform elevation, and extending in straight or curved lines, sometimes zigzagging across the country, almost diametrically outlining the position of the resistant beds and their variation in dip.

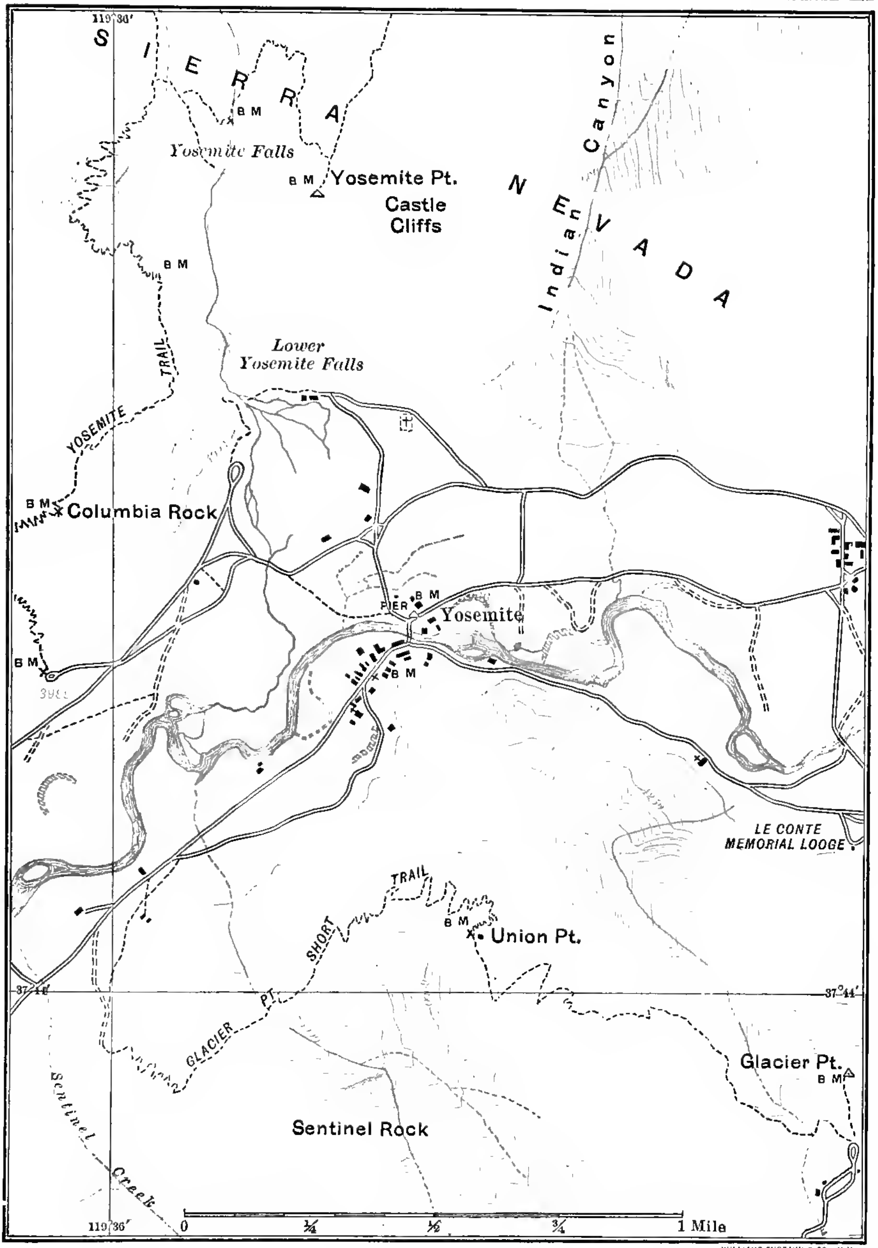
Peaks. — The resistance to denudation of less regular beds gives rise to peaks of infinite variety of form. Sometimes a row of peaks is really a ridge, dissected transversely by more effective denudation along joint plane areas or because of some other favourable condition. More commonly the rocks are locally resistant, or local erosion has removed the rocks round about, giving rise to the peak form. At times the variations in rock resistance are in such limited areas that the peaks are needle-like, or horn-like; but, on the other extreme, they may be of sufficient area to give rise to dome-like peaks. There is every gradation in these residual forms of elevation, from the dome to mere pinnacles a few feet across at the base and a few feet in height.

Dome-like peaks are very commonly due to the presence of coarsely-crystalline, granite rocks, parts of the batholitic intrusion into the core of mountains. Being durable, such rocks resist denudation far more than most rocks and especially sedimentary strata. Thus, when these weaker rocks are stripped away, single peaks, or groups of peaks, remain standing above the general level to which the weaker rocks have been lowered — as in the cases of the Adirondack Mountains of New York and the Black Forest of Germany. Hundreds of mountain peaks are underlain by granitic rocks — Pike's Peak, Mount Washington, Mount Mitchell, and neighbouring peaks are instances in the United States, while the Scandinavian upland and the Scottish High-

FIG. 360. — Erosion forms similar to the Dolomites. Rocky Mountains of Glacier National Park, Montana.

lands furnish instances in Europe. Similar cases abound in other mountain areas of the world.

In these regions of granitic rock, stratification planes are absent, but joint planes serve as guides to the work of denudation. Their influence is very clearly seen in the Sierra Nevada, especially in and near the Yosemite Valley (Pl. IX). The granite is crossed by two sets of nearly vertical joint planes, irregularly spaced, but crossing each other at approximately right angles. There is a third set more nearly horizontal, but gently curved, so that the rock is traversed by a series of concentric planes. As a surface wears down by denudation, these joint planes exert a profound influence on the topography. Weathering, running water, and former glaciers have all been at work modifying the mountain form, and all have been guided in their work through the weakness introduced by the joint planes. The granite has peeled



YOSEMITE VALLEY

A mountain valley in the Sierra Nevada of California which was deepened and had its walls over-steepened by glacial erosion. Yosemite Falls at lip of hanging valley. Contour interval 50 feet. (From map of Yosemite Valley, United States Geological Survey.)

off along the concentric joint planes, as the layers of an onion may be peeled off, and curved outlines and dome-like peaks have resulted. Indeed, some of the most prominent topographic forms of the Yosemite Valley region are called domes. There are also half domes, where a dome is bisected by the stripping away of the rock along one of the vertical sets of joint planes. There are also great precipices, determined by the removal of rock along these vertical planes of weakness; and there are notches excavated where a number of vertical joint planes close together have permitted more rapid denudation. The whole topography is determined by the massiveness of the rock and the joint plane weakness, worked upon by weathering, stream erosion, and glacial erosion.

In regions of generally horizontal structure of well-jointed sedimentary rocks the peaks are apt to develop a castellated form. This is typical of the eastern limestone Alps, which are known as the Dolomites. Such castellated forms are also found in the mountains of the Glacier National Park in Montana (Fig. 360), and their northward continuation in the portions of the Rockies and Selkirks along the Canadian Pacific Railway.

There are a multitude of influences at work determining mountain peak form, only a few of which are outlined in the preceding paragraphs. They are all denudation forms, but there are various combinations of denudation and rock structure and position and, consequently, an almost infinite variety of peak form. With the exception of volcanic cones, mountain peaks are not of constructional origin, but are a phase of the destruction of mountains. Elevation has not caused them, excepting in so far as it has given the opportunity for the agents of denudation to sculpture the elevated complex.

Mountain Valley Forms. — Perhaps the most characteristic feature of valley form in lofty mountains is the gorge, with its associated precipices. This characteristic is due to the fact that the land is high, thus giving rise to steep slopes, while water and sediment load are abundant. The elevation above baselevel, which furnishes the opportunity for gorge cutting, is due to the recency of the uplift, which, as we have seen, is still in progress in many lofty mountains. Such mountains are, therefore, young land forms and the streams are in the stage of youth and busily at work in the attempt to reach grade.

From the gorge stage there is every gradation among mountains to the broadly open valley with moderate slopes; but by far the greater number of slopes among mountains are steep, because of the great mass of elevated land that must be removed by denudation. Therefore, even in mountains that have long since ceased to rise, valley sides are steep; and in young mountains they are prevailingly steep and even precipitous.

Glacial erosion has sculptured valleys in the high mountains of all parts of the earth, and has given rise to a series of topographic forms so characteristic that they are easily recognized. In the higher parts amphitheatre-like valleys or cirques have been excavated, bordered by very steep walls; and, by the recession of cirque heads (Fig. 358), sharp arrêtes have been developed. Farther down U-shaped valleys have been excavated, bordered by steep walls, frequently precipitous on both sides, but sometimes steeper on one side, against which the glacier was cutting most effectively. Such valleys are often straight and canal-like, where powerful glacial abrasion has smoothed off all the valley side irregularities, and even worn off the projecting spurs that are normal to stream-made valleys. The steepened slope of glacial erosion origin grades upward into the more irregular and, often, less steep slopes of the upper valley walls, where glacier scouring did not reach.

The floors of main glaciated valleys often have giant steps which are evidently due to differential glacial erosion. Where two glaciated valleys of about the same size come together there may be a step up to the mouth of each one. This is called a *confluence step.*

Tributary valleys to these troughs of glacial erosion commonly enter at levels well above the trough bottom. From these hanging valleys the water descends either through narrow gorges with torrential velocity, as in so many cases in the Alps, or by direct fall down the steepened slope, as in the Yosemite Valley, in parts of the Alps, and in all other mountain regions of former vigorous glacial action. Along the flattish floor of the glaciated troughs exist many lakes, some of them behind barriers caused by glacial deposit, others in depressions locally scoured out by glacial erosion, even in rock basin depressions. The Italian Lakes on the south side of the Alps are instances of such lakes in depressions deepened by glacial erosion, though dammed also by glacial deposit; and in the Alps there are many small lakes which are true rock basins.

Mountain Passes. — While resistant rocks are left as ridges and peaks, weaker rocks are worn down to form depressions. If the weak rock has considerable linear exposure, the resulting depression is a linear valley; if it is more localized, the depression is more restricted. A great number of depressions in mountains, which, because of their lowness, offer a route, or pass, across them, are due to the local lowering of the surface where weaker rock occurs. It may be a thin-bedded stratum in the midst of more massive and more durable strata that gives rise to a pass; or a weak igneous rock, crossing massive granitic rock; or an area of abundant joint planes or of crushing; or some other structural weakness.

There are other causes for passes, often effective because of local weakness of the mountain rock (Fig. 361). For example, a glacier, flowing over a low portion of a mountain ridge, may so lower the mountain along its course as to leave a pass on the disappearance of the ice. A river crossing a mountain ridge or range, perhaps along a zone of weakness, forms a valley which may serve as a pass. Again, a mountain river, gnawing at its headwater, may push the divide back and

Fig. 361. — Roads zigzagging back and forth to cross the passes of the Alps near Rhone Glacier. Furka Pass to the right of the glacier. Grimsel Pass to the left, with an ascent of nearly 3300 feet from the valley bottom.

gradually encroach upon the valley of a stream flowing on the opposite side of the divide. By such headwater erosion the upper tributaries of the opposing stream may even be captured, and the divide pushed back to the opposite side of the ridge or range, thus forming a notable gap in the mountain which becomes a good pass. The Maloja Pass in Switzerland has been explained in this way, the stream on the southern or Mediterranean side, because of its steeper, more direct course, having eaten its way back and captured headwaters of the Inn River, so that a very low, flat-bottomed pass exists, with a steep slope on the Mediterranean side. In many mountains the pushing back of headwaters, especially along zones of weak strata, has gone so far that the stream source is pushed across the mountain and its valley has become a pass. There are also passes which follow the valleys of antecedent streams across mountains.

Mountain Deposits. — The waste from the wearing down of mountains is mainly distributed far and wide by the streams that radiate from them; out of this waste are built intermont plains and other deposits, and extensive deposits in lakes and ocean. Some of it, however, comes temporarily to rest within the mountains, giving rise to characteristic local topographic features. At the cliff base are extensive talus deposits, some steep and bare of vegetation, others more gently sloping and forest-covered. The talus slope is one of the significant features in mountain landscape; it is a curve or slope of deposit, often contrasting strikingly with angular outlines above where sculpturing is in progress.

Avalanche Deposits. — Here and there are avalanche deposits, great streams of rock fragments, sometimes hummocky in topography. When freshly fallen they are barren belts, forming great blotches in the landscape, perhaps in the midst of fields or forests through which they plunged in their destructive downward course. In such cases, too, there is, on the mountain face, the fresh scar, caused by the avalanche downfall. In time the avalanche becomes clothed with vegetation, and the mountain side scar is partly obscured by new growth of vegetation. Mountain sides reveal many such avalanche scars in various stages of healing and at the base of the mountain slopes are to be seen the rock streams and avalanches that descended from them.

Alluvial Fans. — Alluvial fans, often with steep grade, are common in the broader mountain valleys, where the mountain streams emerge with high velocity and abundant sediment load, some of which must be dropped on the gentler slopes of the main valley. Such alluvial fans exist by the thousands in the Alps and in other mountains; and their graded slopes are often the sites of villages.

Glacial Deposits. — Where the mountain valleys have been occupied by glaciers, their sides and bottoms may be veneered with ground moraine, and dotted with boulders of rock varieties common higher up the valleys. Lateral moraines may fringe the valley wall, and terminal moraines with hummocky topography may sweep across the valley in crescentic curve. Outwash gravel plains may occupy the valley bottom, raising and levelling its surface, and perhaps carved into terraces by stream erosion, subsequent to the time of deposit when the glacial streams were flowing.

Glacial deposits, and sometimes avalanches, have caused obstruction to mountain drainage and, thereby, given rise to lakes, some merely pools, others of good size. Such lakes, as well as those in rock basins, become the seat of deposit of sediment transported by the mountain streams. In a region of such active denudation, lakes are commonly filled with rapidity, as such work goes. Thus it is that there are many flat-surfaced meadow areas where lakes once existed, and many others where lakes are partly filled. Extensive fan-shaped deltas are built out into the sides of the deeper ones, while, at their heads, the inlet streams are commonly bordered by extensive delta flats and marshy lands, contrasting strikingly with the rugged topography of the encircling mountain walls. Frequently these delta areas are the only level land in the neighbourhood, and upon them the villages of the region have grown.

Cycle of Mountain Development

Sculpturing during Uplift. — During the period of active growth, mountains continue to rise differentially, and faster than denudation can lower them. They become steadily higher, though there seems to be a limit beyond which they cannot be reared. During such growth some parts are raised higher than others by folding or faulting, and probably neighbouring parts are lowered. Earthquakes are developed during the movements and volcanic outbursts may occur in association with the uplift. The result is the formation of a range or a system of individual ranges and ridges, with valleys between. Associated with the localized folding or faulting may be broad uplift without notable disturbance of the strata, giving rise to a plateau, and the plateau uplift may even be the grand feature of the uplift, while the mountain range is but a local disturbance in it.

If there were no denudation on the earth, the mountain form thus produced would be notably irregular as the direct result of differential folding and faulting; with denudation its irregularity is greatly increased, though its elevation is diminished. Since mountain growth is slow, while the activity of denudation is increased by the elevation, the result of denudation is to greatly sculpture the mountain form, even during the period of its uplift. Thus it is that lofty mountains are so rugged, — a combination of original elevation and irregularity with the sculpturing by denudation superimposed upon it. All lofty rugged mountains are in the stage of youth, and most, if not all, of them are still growing.

Young and Mature Mountains. — Such mountains are characterized by peaks and rugged ridges; and by precipices and gorge-like valleys. They are the seats of active denudation, and, if growth ceases, the denudation operates here, as on all other land forms, (*a*) to reduce the valley bottoms to grade; (*b*) to broaden the valleys and lessen the slopes of the valley walls; and (*c*) to remove the interstream areas. Thus the mountain elevation diminishes, its ridges and peaks are lowered, and its valleys are broadened. It passes through the cycle of maturity and into old age. The mountains of Scotland, of Scandinavia, the Black Forest and the Vosges, the mountains of New England and the Adirondacks, are all in the stage of topographic maturity. They are not low, with moderate slope, because made that

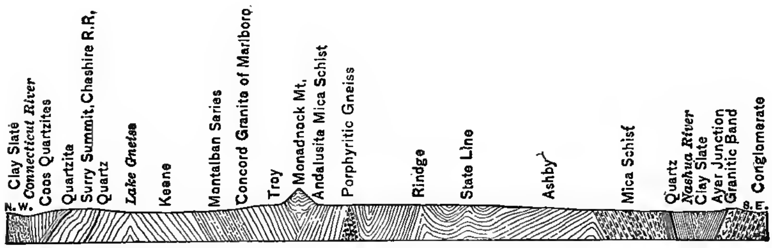


FIG. 362. — Geological cross-section of the peneplain in New Hampshire near Mt. Monadnock, showing the indifference of topography to structure during old age in the mountain cycle. (Hitchcock.)

way by uplift, but because reduced to that condition by long-continued denudation.

Mountains in Old Age. — Further lowering may continue, theoretically, until the former mountain is reduced to the level condition of a plain, in which the influence of the underlying complexity of rock structure no longer exerts appreciable influence upon the topography. There are no known instances of this extreme, which has probably rarely, if ever, been attained over any considerable area of the earth. But an approach to this stage of extreme old age has been reached by numerous mountain regions during their past history. Such an old mountain, worn down to such low relief as to approach the condition of a plain, is a peneplain. On the peneplain, the surface swings up and down, with the sites of the more resistant layers still marked by low swells, or by much reduced peaks. Such reduced peaks, or hills, rising above the peneplain level, have been called *monadnocks*, after Mount Monadnock, which is interpreted as such a residual, rising above the ancient New England peneplain (Fig. 362 and Pl. X).

Illustrations of Peneplains. — Old-age mountains, in the peneplain stage, are well represented in the United States in the Lake Superior region (Figs. 363, 364), the Piedmont Plateau, and the low, hilly country extending northeastward past Washington, Philadelphia, New York, and Boston. From the structural features of the rocks along this belt the inference is warranted that at an earlier geological period there

FIG. 363. — The peneplain of the Lake Superior region, with Jasper Peak, a monadnock.

arose here a truly lofty mountain range, now so reduced that it is the seat of an abundant population, and of some of our largest cities. Other peneplains now uplifted and dissected have been described from numerous regions. One of the best instances of these is in the Rhine

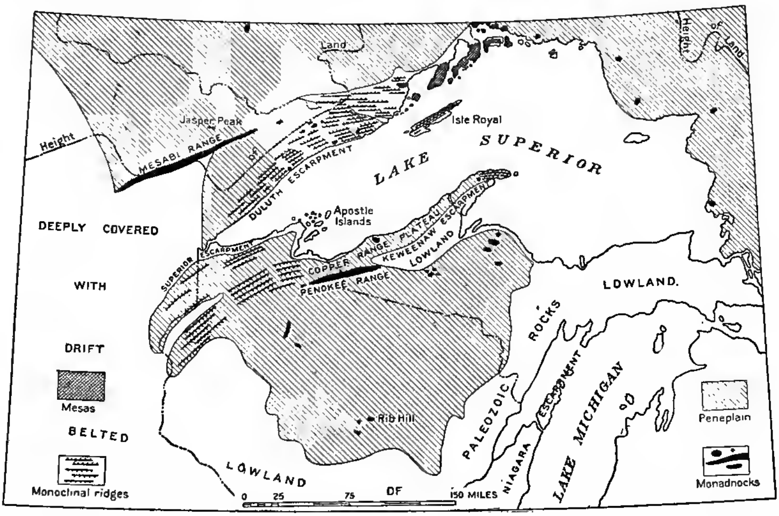


FIG. 364. — Map of the peneplain of the Lake Superior region, with monadnocks rising above the general level, and monoclinal ridges and mesas carved in the slightly dissected upland.

valley of Germany, where the strata are in the characteristic position and condition of mountain rocks, but the upland surface is a moderately undulating plateau, with some elevations of greater height where the strata were more resistant. Recent uplift has permitted the Rhine and other rivers to sink their valleys into the peneplain and it is now beginning to be redissected, but extensive tracts of the ancient peneplain remain. The more mountainous parts of New England, and in fact the entire Appalachian belt, are interpreted as an uplifted and much more dissected peneplain, and the same interpretation, with greater or less degree of probability, has been given to many mountain areas.

Revived Mountains

The Effect of Uplift. — If a mountain is greatly reduced, even though to the state of a peneplain, subsequent uplift without accompanying folding and faulting gives opportunity for the development of mountainous topography. Ridges may be etched out again, peaks may develop, and, if the uplift is great enough, a topography of such great ruggedness may be carved that it is difficult or even impossible to distinguish the revived or rejuvenated mountain from a young mountain of recent uplift. Some inherited features may remain, such, for example, as remnants of the former peneplain surface, or rock terraces marking the sites of former valley bottoms, or incised meanders, developed when the streams swung in curving course over the peneplain surface. The forms developed in the revived mountain will vary in nature and in intensity, according to (1) the amount of the uplift, (2) the nature of the rocks, (3) the length of time that denudation has been at work in sculpturing the area.

Illustration from Germany. — The uplifted peneplain of central Germany may be taken as a typical instance of an early stage in revival of a mountain region by uplift. In it the dissection has gone far enough for the development of gorges along the major streams, and some sculpturing of the complex mountain rocks near them. But between the streams is a broad, swinging upland surface, level enough for farming, and the broad bottoms and general slopes of the old valleys of the peneplain stage are still traceable, while the streams now sunk in the peneplain are flowing in meandering course, giving perfect illustration of incised meanders.

The Second-Cycle Appalachians. — The Appalachian mountain system will serve as a typical instance of a revived mountain range of more mature dissection. These mountains were upraised in early geological ages, forming a very lofty range, and the strata were folded, crumpled, and faulted in intricate manner, while batholitic intrusions rose into the mountain core, and volcanic rocks poured out at the surface. There were subsequent uplifts also, but the last one, at the close of the Carboniferous Period, involved not only the ancient mountains, but extended westward and raised in a series of folds with some faulting, a great thickness of sedimentary strata. Thus the Appalachian system includes two quite opposite types of mountain structure, one, in the west, with moderately folded sedimentary strata, the other, in the east, a complex of sedimentary, metamorphic, and igneous rocks.

Both these areas were worn to a condition of slight relief, and it was from a study of a part of this region that Davis conceived the idea of the peneplain. Subsequent to the peneplain stage there has been uplift, with some warping, and probably with some folding and faulting, so that the upraised surface is higher in some parts than in others. Thus, the Piedmont Plateau is still low and fairly even, while the neighbouring Blue Ridge rises to mountainous height.

Denudation has cut into the uplifted peneplain, but there is still a fair degree of uniformity of the crests, which are interpreted as rem-

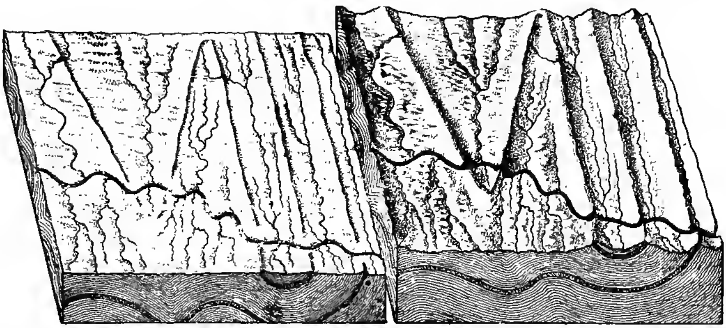


FIG. 365. — At the close of the first cycle the ridges were worn so low that the streams crossed them, but after an uplift (right-hand diagram) the ridges were etched out into strong relief in the second cycle, the streams still maintaining their courses across them. Convergence of ridges due to inclination, or pitch, of axes of folds.

nants of the peneplain. The crystalline rocks have been greatly sculptured, and there is a maze of peaks and intervening valleys, but the stage of reduction in the main cycle has gone so far that the slopes are reduced to the condition of early maturity. The mountains are, therefore, not notably rugged.

In the western folded Appalachians, the evidence of the former peneplain condition is even more clear. The ridges etched into relief rise to a remarkably uniform elevation, in some cases extending for miles in straight course with little break in the evenness of the skyline. Between the ridges are linear valleys of considerable breadth along the belts of weaker strata, and, in some of these, the streams have the meandering course of entrenched meanders, a condition which could only be inherited from a former state of floodplained valley bottom such as would exist on a peneplain surface.

Many of the streams, even small ones, cross the ridges, flowing in narrow gorge-like valleys, known as watergaps. These valleys have been sunk in the ridges by the downcutting of the streams, and time enough has not elapsed for the valley walls to broaden out, as has been the case in the weaker strata. Some of these courses across ridges, notably of the smaller streams, are apparently inherited from the earlier peneplain stage when the ridges stood out in less relief, and the streams flowed over resistant rock layers, later discovered by denudation and etched out into relief, while the superimposed streams continued their course across them, cutting the gorge-like gaps (Fig. 365).

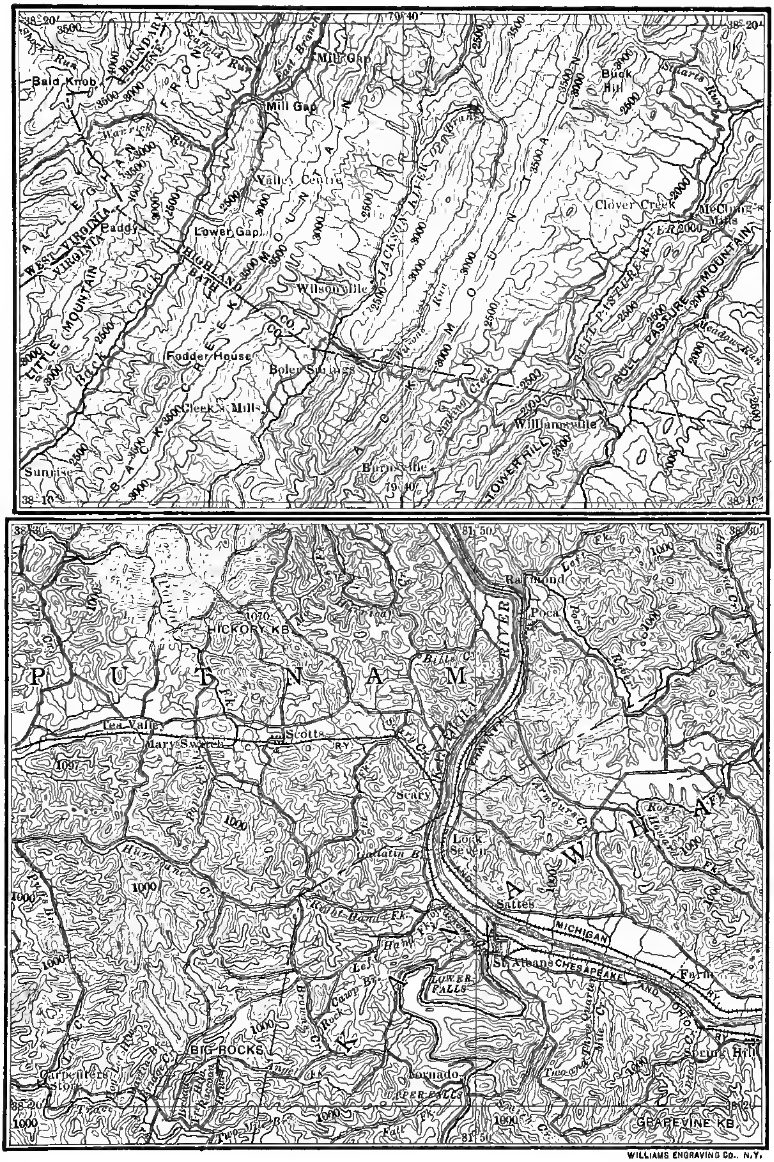
The even-crested Appalachian ridges, etched into relief in the second cycle, are determined by resistant rock layers in pitching folds. The pitch of these folds, therefore, carries some of the pairs of ridges, determined by the outcrop of the same resistant stratum on the two sides of a syncline or anticline, below the present baselevel, so that the ridges die out. This is where the ridges are diverging. Where they converge, as in a pitching synclinal fold, two ridges will come together, forming a *canoe-shaped valley* (Fig. 365). The zigzag character of the Appalachian ridges is, therefore, due to the fact that erosion is etching into a series of pitching folds.

Rocky Mountains. — Even the Rocky Mountains of Colorado, and possibly other parts as well, are revived mountains, though in this case probably accompanied by a greater measure of differential uplift than in the cases already described. Portions of the old, reduced surface still remain as upland plateaus, separated by broad valleys or basins of downfolding, in the Parks; but the streams have sunk deep, canyon-like gorges, such as the Royal Gorge of the Arkansas (Fig. 357); weathering has roughened some of the upland; and glacial erosion has introduced its characteristic elements of sculpturing, notably the cirques and the U-shaped valleys. The same condition is found in the Cascades and many other mountains now in their second cycle.

Mountain River Valleys

Complexity of Mountain Drainage. — If a river flowing upon a surface which is raised into mountains persists in its course, it is an antecedent stream (p. 191); or, if a stream in its downcutting discovers a mountain structure, as at Grand Canyon, it is a superimposed stream (p. 184). Otherwise, mountain drainage is developed as a result of mountain form or structure and has characteristics dependent upon these conditions. Naturally, in a region of such complex structure and such irregularity of form the drainage characteristics are varied and complex. Only part of the elements involved, and a few of the characteristic results can be considered here.

Radial Drainage. — From a dome-shaped mountain, such as a laccolite, the consequent drainage is radial, as on a volcano. Radial drainage of subsequent origin also develops in connection with the sculpturing of peaks. This fact tends to preserve the peak form, for, entirely aside from its extra resistance to denudation, since it is a watershed, stream erosion is reduced to a minimum.



WILLIAMS ENGRAVING CO., N.Y.

FIG. 366. — Topographic maps to show types of drainage in the Appalachian Highland. Upper map shows longitudinal and transverse valleys and trellis drainage, while lower map shows insequent dendritic drainage. (Monterey, Va., and Charleston, W. Va., Quadrangles, U. S. Geol. Survey.)

Longitudinal and Transverse Drainage in Mountains. — In linear mountain forms the drainage normally finds its way by short courses down the slopes into and along linear valleys occupied by longitudinal streams; while here and there escape is found across a low portion of a ridge or around the end of a ridge to another valley. Such transverse streams usually form a small proportion of the total drainage, though they are often conspicuous because of the deep gorges they cut across the ridges. Consequent drainage of this type is well developed in the Jura Mountains of Switzerland and France. It consists (1) of numerous short streams of steep grade from the valley sides, (2) longer, roughly parallel streams in the valleys between the ridges, and (3) occasional transverse streams in gorges (Fig. 366).

Subsequent stream courses of similar habit also develop during the denudation of mountains, as is typically illustrated in the western

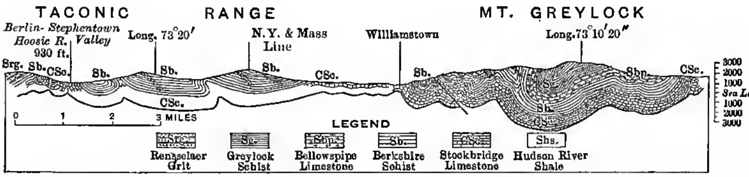


FIG. 367. — The synclinal, schist mountains and anticlinal, limestone valleys of the Appalachians of western Massachusetts. (Dale.)

folded Appalachians. Here the ridges etched out in the resistant rocks are left as divides, from which short streams descend to longitudinal valleys etched out in the weaker strata. These short streams have a steeper course on the outcrop side of the ridge-making rock and a longer slope on the opposite or dip side, the length of the slope depending, in large measure, on the inclination of the strata. A similar condition of drainage, of consequent type, occurs on fault block mountains, where the steep slope is on the side of the fault, and the greater slope on the side toward which the block inclines.

Adjustment to Rock Structure in Mountain Drainage. — Whatever may be the original consequent course of drainage in a mountain region, there is, as denudation lowers the mountain, a constant tendency for the streams to adjust themselves to the rock structure discovered, and, therefore, to develop subsequent courses, as already explained (pp. 184–185). There is every reason to believe that, if one could observe the succession of events during the reduction of a mountain mass, one of the most striking features would be the steady shifting of drainage lines as variations in the rock structure are being revealed. The extent to which such changes may occur can best be understood by considering two cases, both finding illustration in the folded Appalachian Mountains, which have gone through one cycle of denudation and are now well along on the second.

Synclinal Mountains. — In the Appalachians, and in other parts of the world, there are mountains whose summits are synclines, and valleys whose structural features are anticlines. This is a complete reversal of the normal condition as typified in the Jura, where the anticlines are the ridges, and the synclines the valleys. Such reversal is apparently due to the operation of the law of monoclinal shifting

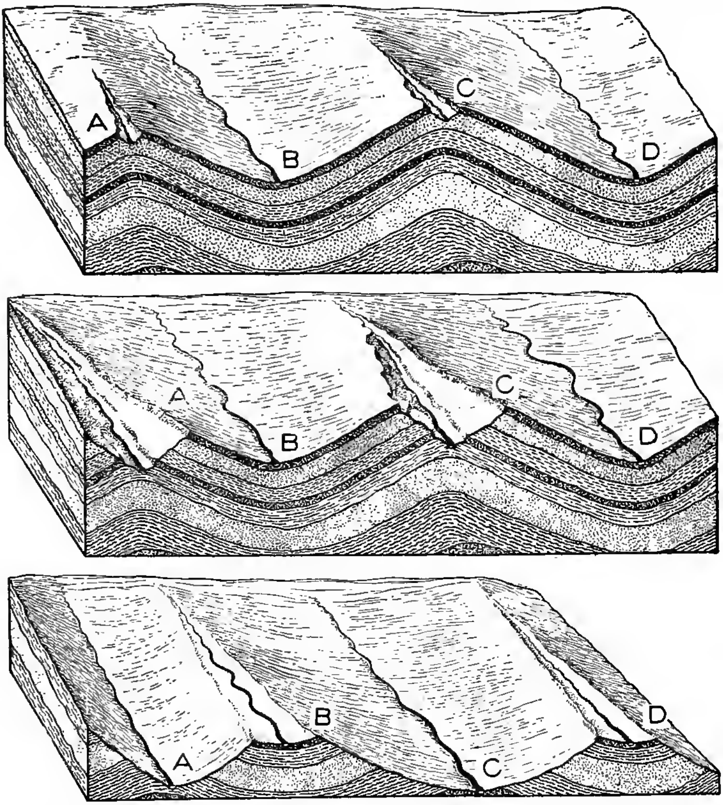


FIG. 368. — Block diagrams to show the evolution of synclinal mountains (*B*, *D*).

(p. 547); that is, that a divide located upon an inclined stratum will migrate in the direction of the dip as the surface is lowered.

This may be illustrated in its application to the formation of synclinal mountains, by considering a simple, theoretical case (Fig. 368). Assume a syncline bordered by two anticlines, the syncline being a valley, the anticlines ridges. Assume, further, resistant surface layers on both syncline and anticlines and weaker layers beneath. If for any reason, such as fissuring along the tops of the anticlines or because denudation operated more rapidly there, on account of superior elevation or any other cause, a longitudinal stream should begin to cut into the top of the anticline, the underlying weak layers would be exposed to denudation on the anticline crest before they were in the syncline depression. When the resistant upper layers were thus breached, the anticline crest would be transformed to two ridges, each inclining away from the crest. Between them would be a valley whose bottom was in the weaker layers and whose sides were the steep, outcrop faces of the resistant, ridge-forming layers. As the surface lowered the ridge crests would migrate in the direction of the dip, that is, toward the syncline valley; and this lowering would be accelerated by sapping as the weaker, loose layers were removed. Thus the syncline valley is made to steadily lose drainage area, while the anticlinal crest valley makes a corresponding gain. With a continua-

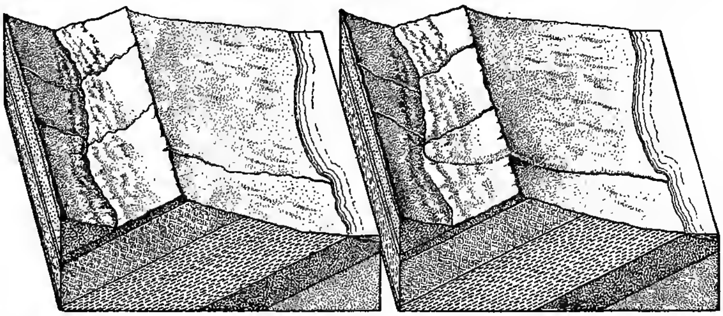


FIG. 369. — Stream diversion and the migration of a divide because the river pirate has a short course to the sea.

tion of the process the synclinal valley is narrowed, and its stream loses power, while the anticlinal valley broadens, its stream gains more volume and power, and it is cut deeper. The ultimate result may be, what is commonly observed in nature, a synclinal mountain and an anticlinal valley, — water flowing along the line of former elevation, and a mountain extending where in the earlier stages water flowed in a linear valley. The beginning of such anticlinal valleys is to be seen in the Jura, where valleys are opening along the crests of arched folds. Fully developed synclinal mountains are found in the Appalachians (Fig. 367).

Migration of Divides in Mountains. — A second feature illustrated in the Appalachian mountains is that of migration of drainage by headwater erosion. There can be little doubt but that, when the Appalachian Mountains were elevated, the main drainage extended from some medial portion of the mountains, some eastward, some westward. The exact site of this ancient divide cannot now be determined; but it seems quite improbable that it lay even approximately along the line of the present divide, for some of the streams head far back in the mountains, and others even in the plateau on the western side; such, for instance, is the case with the Susquehanna River. Proof of exactly what happened to establish the present divide is lacking. Doubtless the process was both a long and a complex one; but it is exceedingly probable that headwater erosion was an important element in the migration of the divide.

Again, to illustrate the process, we may revert to an hypothetical case (Fig. 369). Assume that streams flowing eastward descended by short courses to the ocean, while those flowing westward reached the ocean only after passing over long, roundabout courses. The former evidently would have a great advantage and might be expected to push their divides westward, robbing the weaker streams on that side. A similar result would be brought about if there were heavier rainfall

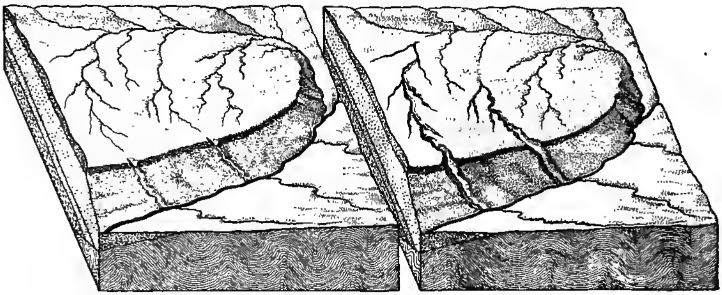


FIG. 370. — Block diagrams to show the origin of the barbed tributaries of certain streams in the Catskills.

on the eastern side, thus giving those streams greater power to eat back at the headwaters.

Diversion of Mountain Streams. — The robbing of streams by headwater erosion is not purely a matter of theory, for numerous instances are now known. The case at the Maloja Pass in Switzerland, where the streams descending by short course to the Mediterranean have robbed the Inn of headwaters that formerly pursued a long roundabout course to the Danube, has already been mentioned (p. 552). Another instance of such a river pirate is found in the eastern slope of the Catskill Mountains, where they rise above the Hudson valley. Two small streams, the Kaaters Kill and the Plaaters Kill, descending this steep slope, have evidently robbed an opposing stream of its headwaters because it could not compete with them for drainage which it had been carrying many miles to baselevel. As a result, the upper course of these small streams receives tributaries pointing westward toward the direction in which they formerly flowed instead of eastward as the lower tributaries do. The tributaries enter in barbed fashion (Fig. 370).

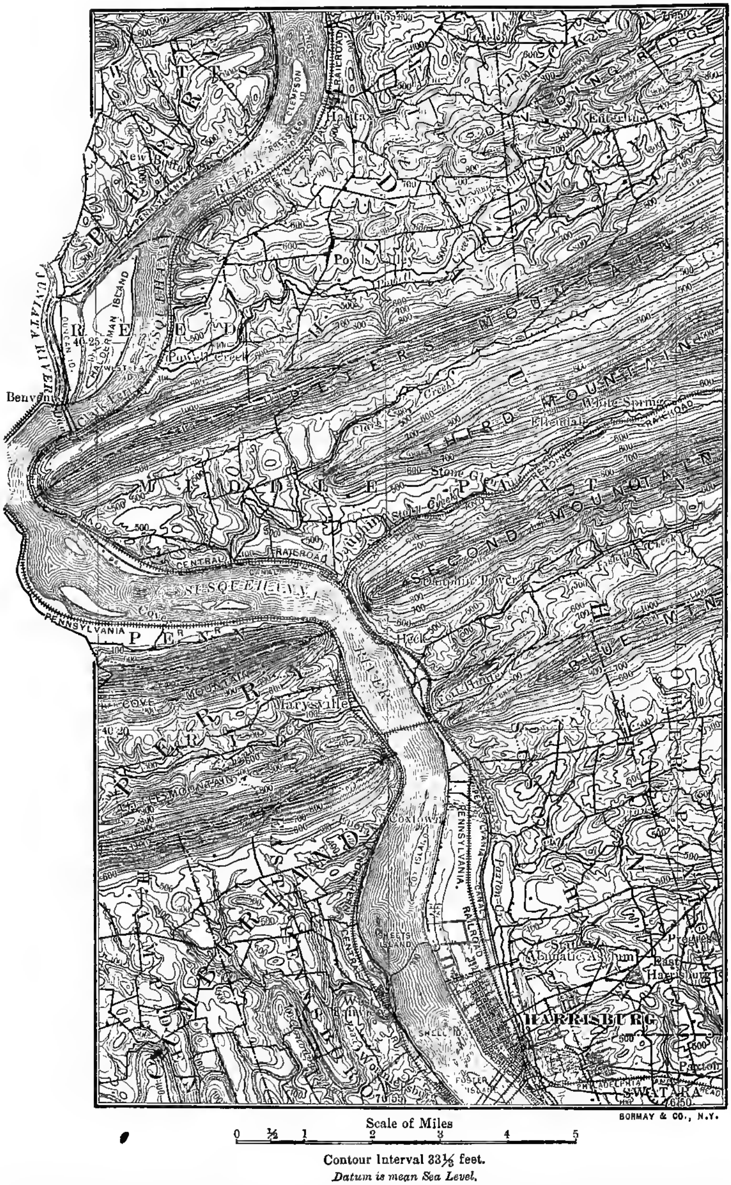


FIG. 371. — Topographic map showing water gaps of the Susquehanna River in resistant sedimentary rock of Blue Mountain, Second Mountain, and Peters Mountain, with broader valleys between in weak rock. Incised meanders in southwest corner of map. (Harrisburg Quadrangle, U. S. Geol. Survey.)

Fig. 372. — The Delaware Water Gap, crossing a ridge of resistant conglomerate in the Appalachians.

River Piracy in Mountains. — The robbery of drainage by an opposing stream or river piracy seems to be common among mountain regions. There are other causes for it besides those mentioned above; in fact, anything that accelerates headwater erosion on one side of a divide, as compared with that on the other side, gives opportunity for the pushing back of the divide and the possible capture of headwaters, or even of good-sized streams, by the successful river pirate. Monoclinal shifting of divides is such a cause, for since the divide migrates in the direction of the dip, the stream on the dip side is open to successful robbery. The presence of a resistant stratum across a stream is another source of weakness in the contest for headwaters. Earth movements also may weaken one stream or strengthen its opponent; and the diversion of streams to other systems may be brought about

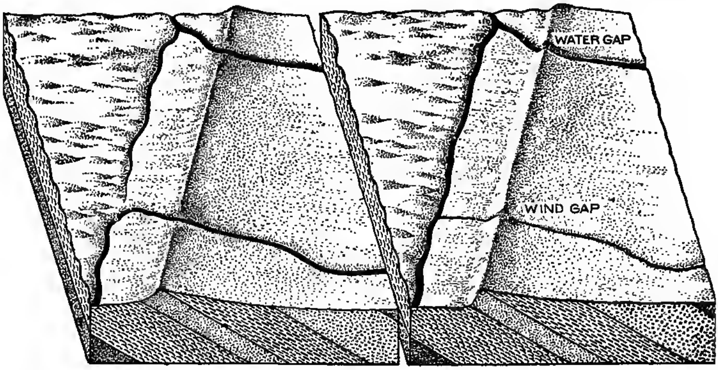


FIG. 373. — Block diagrams to show the origin of a wind gap, as at Snicker's Gap in the Blue Ridge.

or assisted by glacial action, by volcanic deposits, and even by avalanche deposits.

There are thus ample reasons for the migration of divides; indeed the divide that remains in one position as the surface wears down must be the exception, for this assumes a delicate balance of conditions on the two sides. With migration of the divides comes opportunity for river piracy, and it is conceivable that, under favouring conditions, divides may slowly march onward, crossing ridge after ridge even to the opposite side of the mountains, as seems to have been the case in the Appalachian Mountains.

Water Gaps in the Appalachians. — In the Appalachians there are numerous gorge-like valleys where the streams cross the ridges. These water gaps are typically illustrated by the Delaware Water Gap (Fig. 372) or the gap at Harper's Ferry. They may be due to more than a single cause, but the majority are apparently due to the fact that the rivers flowed across the ridges at that earlier stage when the surface was a peneplain and since the uplift which gave the streams opportunity to cut into the ridge, there has not been time for the valleys in the resistant strata to broaden. This illustrates a phenomenon very common among mountains, for valleys frequently broaden and narrow as they extend from weak to resistant rocks. The same valley may have the gorge form of youth in the resistant rocks and be broadened out to the form of maturity where the strata are weak. This is true of the Connecticut River, and Appalachian longitudinal valleys and transverse gaps illustrate this contrast very clearly (Fig. 371).

The resistance to river erosion by the resistant, ridge-forming strata of the Appalachian Mountains has been so great that streams flowing across them have in some instances been captured by more favourably located longitudinal streams. After their capture the gaps through which they flowed still persist, though, by the deepening of the neighbouring longitudinal valleys, as in the Shenandoah valley, often left high above the bottom of these valleys as wind gaps, like Snicker's Gap (Fig. 373), and many others in the Appalachians.

Relation of Mountains to Man

Mountains are, generally speaking, regions of sparse settlement; yet in various respects they have and have had very important influence on the human race. The nature of this influence will be considered under the following headings.

Unfavourableness to Agriculture. — Old mountains may have so level a surface and such a deep cover of disintegrated rock that, like other level lands, they are the seat of extensive agriculture. This is the case in the Piedmont Plateau, a region noted for its cotton and tobacco culture. Young, much-dissected mountains, on the other extreme, are so irregular, there is so much steep slope, and there is so little soil, that agriculture is necessarily limited; and a part of the surface may rise above the zone in which crops can be raised. Here agriculture is confined to the broader valleys, chiefly the longitudinal valleys, and to such slopes as are suited to pasturage (Fig. 374). In mountains between these two extremes are intermediate conditions of agricultural industry; but in none excepting very old mountains is it prominent.

In both the United States and Europe the mountainous sections are predominantly sparsely settled, even where surrounded by dense settlement; and this is primarily because of the absence of the agricultural basis for settlement. This is true, for example, of so reduced a mountain area as the Highlands of Scotland, and the even more reduced mountain area of New England. Local areas, especially the broad valley bottoms, are given over to farming and the slopes to pasturage, but these areas form only a small percentage of the whole, and give basis for only a limited population.

Importance of Lumbering. — In the United States the name Black Hills was given because of the dark colour of the low, forest-covered mountains in the midst of the brown plains; and the name Green Mountains is derived from the colour of the forest verdure. The Schwartzwald, or Black Forest, of Germany, gives another indication of the fact that mountain slopes are commonly forest covered. In the Jura, for example, while there is settlement and farming in the longitudinal valleys, and the more gentle slopes are cleared for pasture, the steeper slopes are prevailingly left in forest.

In some parts of the world the mountain forests have been almost completely cleared away, as in Italy; in others the climate is too

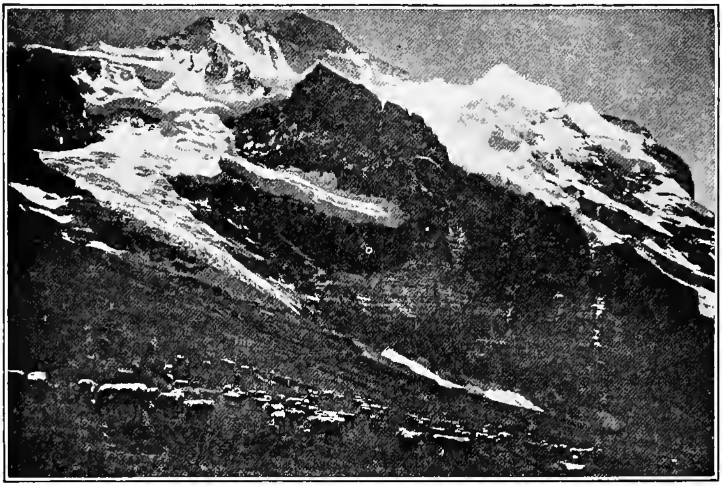


FIG. 374. — High summer pasture on the slopes of the Jungfrau in Switzerland, above timber line and close to the glaciers.

arid for forest growth, as in some of the low Basin Ranges of western United States; and in lofty mountains there are slopes too steep for forest growth, and slopes that rise above the timber line. But, in general, forests clothe extensive areas in mountain ranges. While in places the forest occurs here because the mountains rise high enough to cause sufficient rainfall, in general the presence of forests is not due to any especially favourable condition in the mountains, but rather to the fact that the forest is left here (1) because the land does not pay to clear, (2) because of the difficulties in the way of removing the forest products to regions where needed.

That the first of these conditions is important is indicated by the fact that the Germans, the most scientific foresters of the world, artificially maintain the forest on the low mountain slopes, where the forest products are found more valuable than agriculture. The importance of the second condition is illustrated in newer lands, like the United States. For a long time the mountains of New England, the Appalachian Mountains, and the old mountain region around the western end of Lake Superior were our chief sources of forest products. These sources have now been partly exhausted, though forests still exist in the more remote and more rugged portions. Now the northern Rockies and the Cascade Ranges are being exploited.

The mountains as a natural forest reserve have been of high importance to the United States; and, since they can be continued as a reserve on land that is of less value for other purposes, it is of high importance that the lessons taught by the Germans are now being applied in this country. To maintain and protect the forest means not merely a continuation of the supply of forest products, but also regulation of the streams that drain the mountains and, thereby, a diminution of floods, and a checking of denudation in the mountains, by which weathered rock fragments are removed from slopes, where they are needed, to be deposited in lower areas, perhaps where not wanted.

Importance of Mining. — The name of one of the low, much-worn German mountains is the *Erzgebirge*, a word meaning ore mountains. The same relationship is indicated by the German word *Bergwerk*, or mountain work, which means mining, clearly indicating how closely mining in that country is related to mountains. Throughout the world there is a close relation between mountains and some sorts of mineral wealth. Some kinds of valuable mineral may be found away from mountains, such as coal, clays, and certain building stones; but with few exceptions, the great mining regions of the world are in mountain areas, the chief exception being certain of the deposits of coal. Sometimes the association with mountains is with young mountain areas, but more commonly, with older, much-worn mountains, or with mountains that having passed through one cycle of denudation have started upon another.

The United States, equally with Germany, shows the relationship of mining to mountains. Iron, coal, petroleum, granites, and lesser quantities of other mineral products are found in the Appalachian Mountains and the Adirondacks. The worn-down mountains about the western end of Lake Superior are the seat of the most important iron mining industry in the world, and one of the leading copper deposits. In the western mountains, which rank high among the great mining regions of the world, are produced the bulk of our gold, silver, and copper, besides lead, zinc, and other metals. This mountain mining belt extends northward through Alaska and southward far into Mexico.

Similar relationship is seen in other parts of the world, and one of the chief reasons for settlement among mountains, and the chief reason for towns and cities is the mining industry and the related manufacturing in reducing the ores. Were it not for mining, for example, most of the mountain towns of western United States would not exist and the population would become greatly reduced. The proof of this statement has been given on numerous occasions when the mineral wealth has given out and populous towns have become nearly or quite deserted.

The reasons for the relation of ores to mountains are as follows: (1) lava intrusions or outflows bring to the surface minute quantities of metal, (2) the lava furnishes the heat necessary for water to extract, transport, and deposit these metals in concentrated form in veins, (3) the mountain movements furnish the necessary crevices in which the vein deposit can be made. In some cases not all three of these causes are needed, as in certain iron deposits; and, in some cases, metalliferous deposits can be made away from these favouring conditions, as in the lead and zinc regions of southwestern Wisconsin, southern Missouri, and northern Arkansas. But these are exceptions whose explanation is not difficult, and they do not affect the truth of the general statement. The presence of such mineral deposits in worn-down mountains is due to the fact that denudation has worn the surface down to the zone in which the veins have been formed. Doubtless similar veins lie unrevealed in some mountains, while others that once existed have been worn away as the mountains were lowered.

Limited Manufacturing. — Because of the limited raw products and the sparseness of population, manufacturing in mountain regions is ordinarily not of great importance. Such manufacturing as exists is mainly connected with the leading raw products — those of the forests and the mines. Smelters, stamp mills, and lumber mills are commonly found in mountain regions. Occasionally, too, as in the Appalachians, coal occurs, which gives the fuel basis for other forms of manufacturing.

In the manufacturing, water power from the mountain streams is often of basal importance. Frequently, therefore, a mountain base is fringed with manufacturing towns, as, for instance, in the Adirondacks, in England along the slopes of the Pennine Chain, and along the base of the Alps in Switzerland and in northern Italy. Now that electricity generated by water power can be conducted economically by wire, the extent of the influence of the mountain streams is being extended. It is by no means improbable that in the future the great power which now runs to waste in the mountain torrents will prove a resource of higher and higher value.

Mountains as Resorts. — Mountain scenery is an asset of mountains upon which it is impossible to place a direct money value. Attracted by the fresh air, by the grand scenery, by the invigorating climbs, by the hunting and fishing, by the mineral springs of medicinal properties, people resort to mountains in great numbers, especially in Europe and America. From their sojourns, these visitors reap benefits of various kinds, not the least of which is the mental inspiration which the grandeur of the mountain scenery must give to even the least imaginative.

The attraction exerted by mountains in the respects mentioned has led to so many going to the more accessible of them, that the mountain as a resort becomes really a valuable asset, as in the case of the Adirondack and White Mountains of the United States, the Highlands of Scotland and Wales, and numerous mountains on the continent, especially the Alps. One of the great sources of income to the Swiss people to-day is obtained from the tens of thousands of tourists who flock to the Alps each summer. Paths, roads, and even railways are built to remote and inaccessible points, and hotels are to be found almost anywhere that numbers choose to go. The tourist industry has led to the opening up of much of the Alpine region from France to the far end of the Tyrol, and in summer this mountain range is without doubt the most densely settled, high mountain region of the world. One can scarcely go to any part of the region without encountering others driving, walking, or climbing.

Throngs go to the Hartz Mountains, the Black Forest, the Vosges, and the Jura; but other, more inaccessible, mountains are far less visited. In western United States, for instance, it is only in a few sections that the asset of scenery has as yet become of importance, though one cannot doubt that this is one of the future resources of many parts, as yet known only to the few. Even more true is this of Alaska, whose mountain scenery, excelling in grandeur that of the Alps, is now known to very few, excepting explorers and prospectors.

Mountains as Retreats. — Because of inaccessibility, mountains have, from the very earliest times, served as places of retreat of weaker people before the inroads of stronger ones. Sometimes, too, people are left untouched among mountains by invading hordes who overrun the surrounding lands, but avoid the difficulties of the mountains. A handful of people, knowing the country, can perhaps defend it against a far stronger force, and, if need be, escape by difficult routes unknown to the invaders. The mountain regions of the world furnish numerous instances of the protecting influence of mountains, operative especially in earlier days, but now far less effective than formerly because of the improvement of highways.

In the British Isles, for instance, the Welsh people long resisted successfully the invaders who swept over the more level portions of Great Britain, and they still preserve their primitive language. The Scottish Highlanders also held out against invaders, and were themselves divided into groups, or clans, favoured by the difficulties of access to the deep-set glens and mountain fastnesses. They too have preserved to this day languages and customs of a bygone period, including even peculiarities of dress. Similarly one finds peculiar customs on the continent, — in the Black Forest and the Tyrol, for instance; and also languages of peculiar kind, as in the Alps where Rhaeto-Romansh dialects are found in one part, and in the Pyrenees, where the Basque language still survives, — a language wholly unlike any other known to-day in Europe.

The large number of separate small countries and different languages and dialects in central Europe in earlier days is partly accounted for by the complex mountains there. The greatest number of small states in Germany, for example, are found in the region of worn-down mountains, while the largest states, Prussia and Bavaria, are primarily plain and plateau, respectively. The influence of the mountains in this respect is partly because of the natural boundaries they present, partly because of the ease of defending the mountains or of retreating to the less accessible parts, and partly because mountain land is often not valued highly enough to warrant serious effort to take possession of it and to hold it.

The former importance of mountains in encouraging the existence of independent states is seen to-day in the large number of German states, the different peoples in the Austrian Empire, and even in some survivals of this former state of independence, as Liechtenstein in the Alps, Luxembourg in the old mountain plateau between France and Germany, and Andorra in the Pyrenees. Similarly, in the Himalayas, the mountain state of Afghanistan retains its independence, though encroached upon from the south by the British and from the north by the Russians.

Mountain people are justly credited with high bravery and strong love of liberty, and to these qualities are often ascribed, in part at least, their success in maintaining themselves in their mountain retreats. Such qualities are surely to be expected of people who dwell amidst the grandest of nature's scenery and whose lives are spent in a battle for existence, often against odds, and often amid appalling danger. They must gain a love for their wild mountain home, a strength of mind and body, and a knowledge of their power which would help to rally them in defence of their land. One cannot go much among the mountains without feeling their moral influence.

Mountains as Barriers. — That mountains are barriers to travel is one of the points set forth in the preceding section; otherwise they could not become good retreats. Young transverse valleys and mountain gorges are often too narrow for a path. The frequent use of mountains as boundary lines between nations, as in the case of the Pyrenees between France and Spain and the Andes between Chile and Argentina, shows what excellent barriers they are. They rarely form perfect boundaries, however, for they are pierced by valleys, crossed by passes, and even by streams which head on one side and flow across the entire range, as in the case of the Chilean Andes. As a result, the mountains are often encroached upon from different sides, as the Alps are by France, Italy, Austria, and Germany, besides the central country of Switzerland, whose irregular boundary touches each of these countries, and often along a most artificial line.

Even the Alps have, again and again, proved an ineffectual barrier since the days of Hannibal; and the Himalayas, though they separate two quite distinct ethnic types, and two floras and faunas, have been

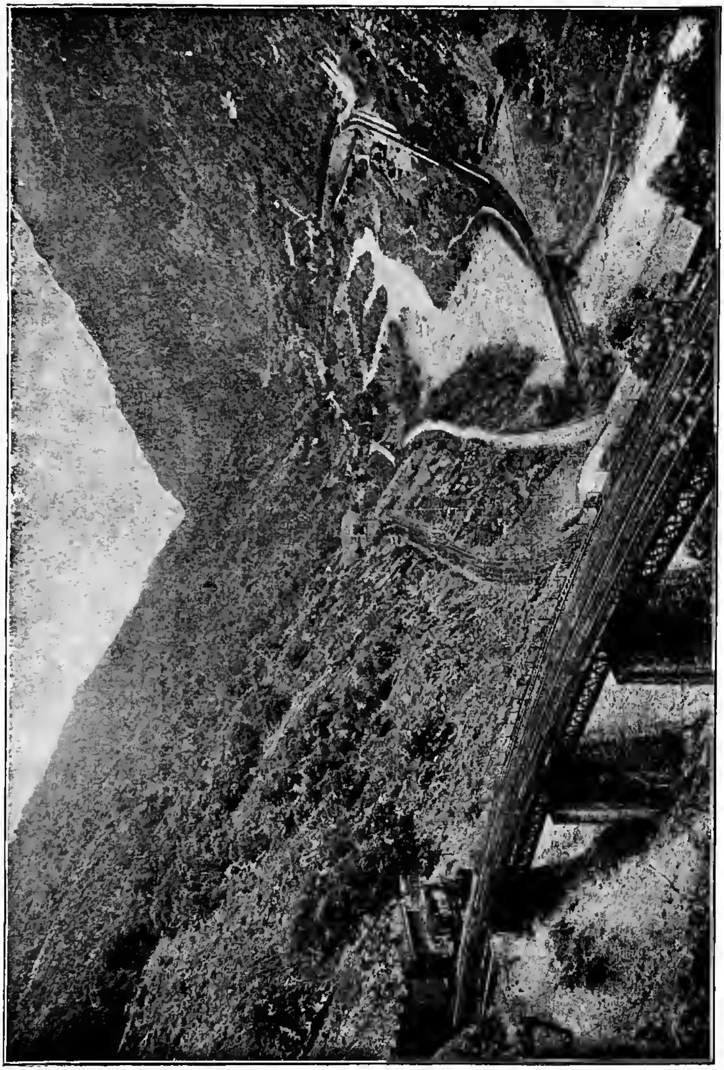


FIG. 375. — A railway crossing the mountain barrier of the Alps. Three levels of the railway leading to the Italian side of St. Gothard Pass. The small spiral tunnels in the mountain side have been partly necessitated through glacial erosion, which leaves tributary streams in hanging valleys instead of the accordant valleys by which railways frequently increase their length in order to gain altitude by an easy grade.

crossed again and again along the weakest part, bringing hordes of invaders into India. Yet, though capable of being broken, and, therefore, not absolute barriers, mountains have seemed greatly to retard the movements of people, and the migrations of plants and animals from the earliest days to the present time. Their ruggedness, the coldness of lofty passes, the forest barriers, and the mountain dwellers have all helped in this interference with migration.

To-day, mountains are far less effective as barriers than they have even before been. Roads, cut in the mountain sides, and built up on steep slopes, rising to the passes in a series of zigzags, now extend in all directions in the Alps. Railways, rising by steep grades, even by

FIG. 376.—The Copper River and Northwestern Railway in the Chugach Mountains of Alaska, where it traverses the stagnant, moraine-veneered, vegetation-covered terminus of Allen Glacier for $5\frac{1}{2}$ miles. There is ice beneath the rails and ties in the foreground.

rack-and-pinion, and piercing the mountains in tunnels many miles in length, connect Austria, Germany, and France with Italy across the Alps. Engineering skill is able to confront even the most serious of mountain obstacles, if the object is sufficiently strong to warrant the expense (Figs. 361, 375).

Yet, how great the barrier is, may be seen from a few examples, from regions where the incentive for human conquest has been less great. No railway has as yet been laid across the Himalayas; and until 1910, no railroad completely crossed the Andes, though several had been built across the outer range. In Alaska the coast ranges form so serious a barrier that the development of the mineral resources has been greatly retarded. A railway recently built through them crosses a large river between two huge glaciers (Fig. 128) which discharge icebergs into the river from vertical ice cliffs, over 200 feet high and three miles or more in length; and, a little farther, extends over the stagnant end of a glacier (Figs. 376, 377), for $5\frac{1}{2}$ miles.

Where mountains rise from the seacoast, they may increase the effectiveness of the barrier by presenting a straight coast line, as in the Andean coast. Or, on the other hand, if subsidence has taken place, or if glacial erosion has worn the mountain valley below sea level, the coast may be greatly indented, as in southern Alaska, British Columbia and Washington, in Scotland, Scandinavia, and Greece.

Even low mountains, especially if young, may be serious obstacles to travel. The Coast Ranges of western United States, for instance, though of no great height, are effective barriers. The coast is prevailingly straight and harbours are few. There is settlement along some of the longitudinal valleys, and lines of travel follow them; but there is almost complete absence of railways across them, and none along their seaward face. In the much higher Andes, also, there is travel and settlement along the valleys, but only at long intervals are there railroads connecting the valleys with the sea. The mountain barrier has greatly retarded the development of the Andean countries, and even valuable mining districts are reached only by rude trails.

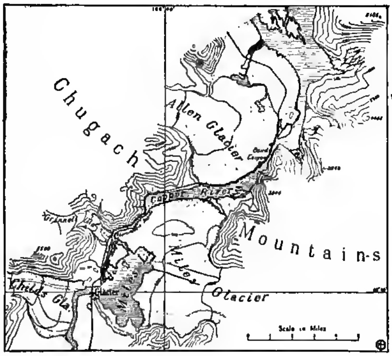


FIG. 377. — A mountain railway in Alaska, passing between two great glaciers and over the terminus of a third.

It might seem that a worn-down mountain region would present little obstacle to travel, but this is far from being the case; for, even when the valleys have broadened out to early maturity, there is still sufficient ruggedness to interfere with travel; and it is often the case that forest tracts also aid in the effectiveness of the barrier. The Appalachian Mountains and the Allegheny Plateau will illustrate the nature of such a barrier (Fig. 378). The barrier long seemed to hem the colonists in along the coast lands; and when the barrier was crossed and settlers occupied the country beyond, they were still so separated from the parent colonies that there was serious effort to set up an independent transmontane country. Now the barrier is crossed by railways at several points, but still there exist in the more inaccessible parts a people who are strikingly out of touch with the modern progress of the surrounding regions.

Effect of Mountains on Climate. — Mountains rising above the general level have a cooler climate than surrounding lowlands. The decrease in temperature with altitude amounts to one degree for every

300 feet. This is equal to going 30 to 60 miles poleward. As the winds rise to pass over mountains they are caused to precipitate some of their vapour, either as rain or snow. This has an important effect, both directly on the mountains, and indirectly on the region near the mountains. The effects on the mountains are (1) the influence of the precipitation on erosion, (2) the development of snow fields and glaciers, and (3) the supply of water necessary for forest growth. The influence on the surrounding country includes (1) the washing down of sediment, which may spread out at the mountain base, (2) the supply

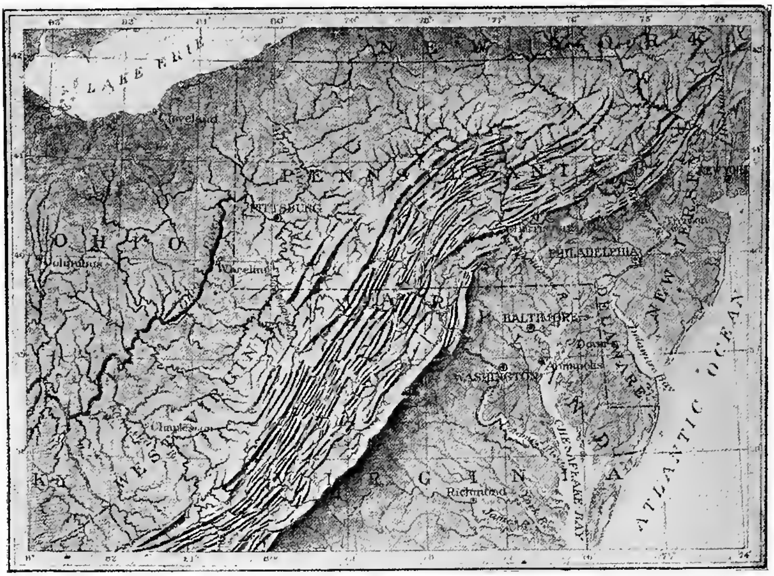


FIG. 378. — The Appalachians as a low but effective mountain barrier. (Willis.)

of water to the surrounding country, and (3) the influence on the climate of the country.

The climatic influence of mountains upon the neighbouring country is effective in several ways, but without doubt the most important is in the reduction of the rainfall. Winds that precipitate vapour on rising over the mountains have less for precipitation in the lee of the mountains, and they may have so little that the country is a desert. The Cascade Ranges of Washington, for example, have abundant rainfall on the western slopes and crests, but are bordered by a desert strip along their eastern base. The central Andes, on the other hand, reached by winds from the east, are clothed with forest on that side, but are a desert on the west. The Himalayas have their rainfall on the south and the desert to the north. The Alps, not lying athwart a prevailing wind system, have no desert, but abundant rainfall on all sides and on all slopes.

Even low mountain ranges over which prevailing winds blow produce an important influence on the rainfall. In the British Isles, for example, the mountains of Wales, the English Lake District, and the western highlands of Scotland have far heavier rainfall than the country to the east, and in places, in the east, as in the neighbourhood of Cambridge, there is very light rainfall. Were these mountains lofty and continuous from Scandinavia to Brittany, there would doubtless be desert conditions to the east, as there evidently have been in earlier geological ages.

The water that falls in the mountains may serve many uses as it flows out over the surrounding country. The Rhine, supplied from the rains and snows of the Alps, and regulated in flow by the mountain lakes, is useful for navigation. A multitude of mountain streams serve as a source of water for power, and for municipal purposes; and, in arid lands, the mountain streams give to the soil by irrigation a part of the water of which the mountains have robbed it. This finds illustration in many places in western United States, as at the Roosevelt Dam in Arizona. Also, large streams may flow long distances, crossing and irrigating deserts far away from the mountain source of the water, as the Nile does in Egypt and the Colorado in California.

Advantages and Disadvantages to Man. — It would be difficult to strike a proper balance between the beneficial and injurious effects of mountains, for there are many factors involved. Mountains greatly decrease the area of habitable land (1) by their own ruggedness and inhabitability, (2) by the aridity to which they give rise. On the other hand, they are a source of valuable mineral products, and out of their elevation and denudation has come a large part of the habitable land of the earth. They are the source of great rivers; but such rivers also develop on plains. They increase the forest area in arid regions, but they also cause such aridity as to prevent forest growth where otherwise it would doubtless occur. They are barriers to travel and trade, but they are also retreats. During the general European war in 1914 the mountains were a positive influence in some respects. During the German campaign against France at the beginning of the war, for example, the mountains helped bring about the invasion of Belgium because the ancient highland of Ardennes is lower and more easily crossed there than in Luxembourg.

Of one point, however, we may be certain; as land forms, the mountains are to be ranked among the least attractive for human occupation. Everywhere, throughout the world, whether lofty or moderately subdued, mountains are prevailingly regions of sparse settlement and relative inaccessibility. They offer a striking antithesis to the level plains, teeming with population, the seat of industry and progress, and the highways of busy trade.

References to Literature

J. Barrell. Central Connecticut in the Geologic Past, Proc. Wyoming Hist. and Geol. Soc., Vol. 12, 1912, pp. 25–54; Bull. Geol. Surv. Conn. (in press).

Isaiah Bowman. Physiography of the Central Andes, Amer. Journ. Sci., Vol. 178, 1909, pp. 197–217, 373–402; Results of an Expedition to the Central Andes, Bull. Amer. Geog. Soc., Vol. 46, 1914, pp. 161–183; Physiography of the United States, Forest Physiography, New York, 1911, — New England, pp. 636–684; Piedmont Plateau, pp. 623–635; Appalachian Mountains, pp. 585–684; Adirondack Mountains, pp. 578–584; Lake Superior Highland, pp. 572–578; Laurentian Plateau, pp. 554–572; Rocky Mountains, pp. 298–404; Basin Ranges, pp. 218–228; Blue Mountains, pp. 207–209; Cascade and Sierra Nevada Mountains, pp. 149–176; Coast Ranges, pp. 127–148.

A. H. Brooks. Geography and Geology of Alaska, Prof. Paper 45, U. S. Geol. Survey, 1906, 327 pp.; Mount McKinley Region, Alaska, *ibid.*, Prof. Paper 70, 1911, 234 pp.

M. R. Campbell. Geographic Development of Northern Pennsylvania and Southern New York, Bull. Geol. Soc. Amer., Vol. 14, 1903, pp. 277–296.

T. N. Dale. Taconic Physiography, Bull. 272, U. S. Geol. Survey, 1905, 52 pp.

R. A. Daly. Physiography of Acadia, Bull. Mus. Comp. Zoöl., Vol. 38, 1901, pp. 73–103; Accordance of Summit Levels Among Alpine Mountains, Journ. Geol., Vol. 13, 1905, pp. 105–125.

J. D. Dana. On the Origin of Mountains, Amer. Journ. Sci., 3d series, Vol. 5, 1873, pp. 347–350; *ibid.*, pp. 423–434, 474–475; *ibid.*, Vol. 6, 1873, pp. 6–14, 104–115, 161–172, 381–382; Characteristics of Some Typical Mountain Ranges, Manual of Geology, 4th edition, New York, 1896, pp. 353–369; Orogenic Work, *ibid.*, pp. 380–396.

N. H. Darton. Shawangunk Mountain, Nat. Geog. Mag., Vol. 6, 1894, pp. 23–34; Examples of Stream Robbing in the Catskill Mountains, Bull. Geol. Soc. Amer., Vol. 7, 1896, pp. 505–507.

A. Daubrée. Études Synthétiques de Géologie Expérimentale, Paris, 1879, 828 pp.

W. M. Davis. Topographic Development of the Triassic Formation of the Connecticut Valley, Amer. Journ. Sci., 3d series, Vol. 37, 1889, pp. 423–434; The Rivers of Northern New Jersey, Nat. Geog. Mag., Vol. 2, 1890, pp. 81–110; The Folds of the Appalachians, Goldthwaites Geog. Mag., Vol. 3, 1892, pp. 251–255; *ibid.*, pp. 343–350; Physical Geography of Southern New England, National Geographic Monographs, New York, 1896, pp. 269–304; The Mountains of Southernmost Africa, Bull. Amer. Geog. Soc., Vol. 38, 1906, pp. 593–623; 10th Census of United States, Vol. 15, 1886, pp. 697–712; Mountain Ranges of the Great Basin, Geographical Essays, Boston, 1909, pp. 725–772; The Wasatch, Canyon, and House Ranges, Utah, Bull. Mus. Comp. Zoöl., Vol. 49, 1905, pp. 15–58; The Rhine Gorge and the Bosphorus, Journ. Geog., Vol. 11, 1912, pp. 209–215; Gebirge, Erklärende Beschreibung der Landformen, Leipzig, 1912, pp. 246–315; Colorado Front Range, Annals Assoc. Amer. Geographers, Vol. 1, 1911, pp. 21–83.

G. M. Dawson. Later Physiographic Geology of the Rocky Mountain Region in Canada, Trans. Roy. Soc. Canada, Section IV, 1890, pp. 3–74; *ibid.*, Bull. Geol. Soc. Amer., Vol. 12, 1901, pp. 57–92.

J. S. Diller. Tertiary Revolution in the Topography of the Pacific Coast, 14th Ann. Rept., U. S. Geol. Survey, Part 2, 1894, pp. 397–434; Topographic Development of the Klamath Mountains, Bull. 196, U. S. Geol. Survey, 1902, 69 pp.

S. F. Emmons. Orographic Movements in the Rocky Mountains, Bull. Geol. Soc. Amer., Vol. 1, 1890, pp. 245–286.

S. F. Emmons and Others. Geological Guide Book of the Rocky Mountain

Excursion, 5th International Geological Congress, Washington, 1893, pp. 255–487.
H. W. Fairbanks. The Physiography of California, Bull. Amer. Bureau of Geography, Vol. 1, 1901, pp. 232–252, 329–353.
A. Geikie. Physiographic Geology, Text-Book of Geology, New York, 1903, Vol. 2, pp. 1363–1388; Continental Elevation and Subsidence, Proc. Geol. Soc., London, Vol. 60, 1904, pp. lxxx–civ.
J. Geikie. Fragments of Earth Lore, Edinburgh, 1893, pp. 36–61; Earth Sculpture, New York, 1898, pp. 92–149; The Architecture and Origin of the Alps, Scottish Geog. Mag., Vol. 27, 1911, pp. 393–417; Mountains, Edinburgh, 1913, 311 pp.
G. K. Gilbert. Mountain, Universal (Johnson's) Encyclopedia, Vol. 8, 1900, pp. 282–284; Orology, Wheeler's Geographical Surveys West of the 100th Meridian, Vol. 3, Washington, 1875, pp. 21–62; Origin of the Physical Features of the United States, Nat. Geog. Mag., Vol. 9, 1898, pp. 308–317.
A. Hague. King's U. S. Geological Exploration of the 40th Parallel, Vol. 2, Descriptive Geology, 1877, pp. 112–129.
F. V. Hayden. Rocky Mountains, U. S. Geol. Survey of the Territories, Vol. 1, 1867–1869, to Vol. 11, 1877.
C. W. Hayes. Physiography of the Chattanooga District in Tennessee, Georgia, and Alabama, 19th Ann. Rept., U. S. Geol. Survey, Part 2, 1899, pp. 1–58; The Southern Appalachians, National Geographic Monographs, New York, 1896, pp. 305–336.
C. W. Hayes and M. R. Campbell. Geomorphology of the Southern Appalachians, Nat. Geog. Mag., Vol. 6, 1894, pp. 63–126.
A. Heim. Der Bau der Schweizeralpen, Neujahrsblatt 110, Naturforschenden Gesellschaft, Zürich, 1908, 26 pp.; Untersuchungen über den Mechanismus der Gebirgsbildung, Basel, 1878, 2 vols. and atlas, 346 pp.
A. Heim and E. de Margerie. Les Dislocations de l'Écorse Terrestre, Zürich, 1888, 154 pp.
W. H. Hobbs. The Origin and the Forms of Mountains, Earth Features and their Meaning, New York, 1912, pp. 435–447; Tectonic Geography of Eastern Asia, Amer. Geol., Vol. 35, 1904, pp. 69–80, 141–151, 214–226, 283–291, 371–378.
W. Joerg. The Tectonic Lines of the Northern Part of the North American Cordillera, Bull. Amer. Geog. Soc., Vol. 42, 1910, pp. 161–179.
D. W. Johnson. Block Mountains in New Mexico, Amer. Geol., Vol. 31, 1903, pp. 135–139.
A. Keith. Geology of the Catoctin Belt, 14th Ann. Rept., U. S. Geol. Survey, Part 2, 1894, pp. 285–395.
J. F. Kemp. The Physiography of the Adirondacks, Pop. Sci. Monthly, Vol. 68, 1906, pp. 195–210.
C. King. Mountaineering in the Sierra Nevada, New York, 1902; U. S. Geological Exploration of the 40th Parallel, Vol. 1, Systematic Geology, Washington, 1878, 803 pp.
A. de Lapparent. De la Classification des Montagnes, Leçons de Géographie Physique, Paris, 1898, pp. 701–718.
A. C. Lawson. Sketch of the Geology of the San Francisco Peninsula, 15th Ann. Rept., U. S. Geol. Survey, 1895, pp. 399–476.
J. Le Conte. On the Structure and Origin of Mountains, Amer. Journ. Sci., Vol. 38, 1889, pp. 257–263; Theories of the Origin of Mountain Ranges, Journ. Geol., Vol. 1, 1893, pp. 543–573.
W. Lindgren. A Geological Reconnaissance Across the Bitterroot Range, Prof. Paper 27, U. S. Geol. Survey, 1904, 123 pp.
G. D. Louderback. Basin Range Structure of the Humboldt Region, Bull. Geol. Soc. Amer., Vol. 15, 1904, pp. 289–346.
M. Lugeon. Les Grandes Nappes de Recouvrement des Alpes du Chablais et de la Suisse, Bull. Geol. Soc. France, Vol. 4, 1901, pp. 723–825; Les Nappes de Recouvrement de la Tatra et l'Origine des Klippes des Karpetes, Bull. Soc. Vaudois Sc. Nat., Vol. 39, 1903, pp. 146–197.

J. E. Marr. The Scientific Study of Scenery, New York, 1900, pp. 55–112.
Lawrence Martin. Physical Geography of the Lake Superior Region, Monograph 52, U. S. Geol. Survey, 1911, pp. 85–117.
E. de Martonne. Recherches sur l'Évolution Morphologique des Alps de Transylvanie, Revue de Géogr. Vol. 1, 1897, 279 pp.
H. Newton. Geology of the Black Hills, U. S. Geol. and Geog. Survey of the Rocky Mountain Region, Washington, 1880, 222 pp.
B. N. Peach and J. Horn. Geological Structure of the North-West Highlands of Scotland, Memoirs Geol. Survey of Great Britain, Glasgow, 1907, 668 pp.
A. Penck. Die Gebirge, Morphologie der Erdoberfläche, Part 2, Stuttgart, 1894, pp. 327–438.
J. W. Powell. Types of Orographic Structure, Amer. Journ. Sci., Vol. 12, 1876, pp. 414–428; Physiographic Features, National Geographic Monographs, New York, 1896, pp. 33–64; Physiographic Processes, *ibid.*, pp. 1–32; Physiographic Regions of the United States, *ibid.*, pp. 65–100; Geology of the Eastern Portion of the Uinta Mountains, Geol. and Geog. Survey of the Territories, Washington, 1876, 218 pp.
R. Pumpelly, J. E. Wolff, and T. N. Dale. Geology of the Green Mountains in Massachusetts, Monograph 23, U. S. Geol. Survey, 1894, 206 pp.
A. C. Ramsay. The Physical Geology and Geography of Great Britain, London, 1864, 1894, 421 pp.
T. M. Reade. Origin of Mountain Ranges, London, 1886, 359 pp.; Evolution of Earth Structure, New York, 1903, 342 pp.
W. N. Rice. The Classification of Mountains, 8th International Geographical Congress, Washington, 1905, pp. 185–189.
H. D. Rogers. The Geology of Pennsylvania, 2 vols., Philadelphia, 1858.
I. C. Russell. Fault Blocks in the Great Basin, 4th Ann. Rept., U. S. Geol. Survey, 1884, pp. 435–464; North America, New York, 1904, 435 pp.
W. B. Scott. Mountain Ranges, Introduction to Geology, New York, 1907, pp. 503–515.
E. C. Semple. Mountain Passes: A Study in Anthropogeography, Bull. Amer. Geog. Soc., Vol. 33, 1901, pp. 124–137, 191–203; Influences of Geographic Environment, New York, 1911, pp. 557–606.
N. S. Shaler. Spacing of Rivers with Reference to the Hypothesis of Base Leveling, Bull. Geol. Soc. Amer., Vol. 10, 1899, pp. 263–276; Broad Valleys of the Cordilleras, *ibid.*, Vol. 12, 1901, pp. 271–300.
G. O. Smith and F. C. Calkins. Geological Reconnaissance across the Cascade Range, Bull. 235, U. S. Geol. Survey, 1904, 103 pp.
J. E. Spurr. Origin and Structure of the Basin Ranges, Bull. Geol. Soc. Amer., Vol. 12, 1901, pp. 217–270.
E. Suess. Das Antlitz der Erde: de Margerie's Translation in French, 5 vols.. Sollas's translation in English, 4 vols., Oxford, Part 1, The Movements in the Outer Crust of the Earth, Vol. 1, 1904, pp. 1–179; Part 2, The Mountain Ranges of the Earth, *ibid.*, pp. 180–604; Part 4, The Face of the Earth, Vol. 3, 1908, 400 pp.; Part 4, *Continued*, Vol. 4, 1909, 673 pp.
R. S. Tarr. The Peneplain, Amer. Geol., Vol. 21, 1898, pp. 351–370; The Mountains — Subequality of Level, The Yakutat Bay Region, Alaska, Prof. Paper 64, U. S. Geol. Survey, 1909, pp. 28–29; Physical Geography of New York State, Chapter III, New York, 1902.
C. Thomas. Hayden's Geol. and Geog. Survey of the Territories, Washington, 1871, pp. 211–216.
W. S. Tower. Regional and Economic Geography of Pennsylvania, Bull. Geog. Soc. Philadelphia, Vol. 4, 1906, pp. 57–76, 113–136, 193–204.
W. Upham. A Classification of Mountain Ranges according to their Structure, Origin, and Age, Appalachia, Vol. 6, 1892, pp. 191–207.
C. R. Van Hise. Relations of Rock Flowage to Mountain Making, A Treatise on Metamorphism, Monograph 47, U. S. Geol. Survey, 1904, pp. 924–931.

S. Weidman. Geology of North Central Wisconsin, Bull. 16, Wis. Geol. Survey, 1907, 697 pp.

J. D. Whitney. The Coast Ranges and Sierra Nevada, Geol. Survey of California, Vol. 1, 1865, 498 pp.

B. Willis. Round about Ashville, Nat. Geog. Mag., Vol. 1, 1889, pp. 291–300; The Northern Appalachians, Nat. Geog. Monographs, New York, 1896, pp. 169–202; Mechanics of Appalachian Structure, 13th Ann. Rept., U. S. Geol. Survey, Part 2, 1893, pp. 211–281; Studies in Mountain Growth, Year Book 4, Carnegie Institution, Washington, 1906, pp. 192–203; Geological Structure of the Alps, Smithsonian Misc. Collections, No. 2067, 1912, 13 pp.; Lewis and Livingston Ranges, Bull. Geol. Soc. Amer., Vol. 13, 1902, pp. 305–352; Physiography and Deformation of the Wenatchee-Chelan District, Cascade Range, Prof. Paper 19, U. S. Geol. Survey, 1903, pp. 41–97; Physiography of Northwestern China, Carnegie Institution, Publ. 54, 1907, pp. 203–264; Physiography of Southern Shen-si, *ibid.*, pp. 319–340.

A. W. G. Wilson. The Laurentian Peneplain, Journ. Geol., Vol. 11, 1903, pp. 615–669.

H. M. Wilson. Topographic Forms of United States, Bull. Amer. Geog. Soc., Vol. 33, 1901, pp. 301–304.

TOPOGRAPHIC MAPS

Adirondacks

Mt. Marcy, N.Y.	Lake Placid, N.Y.	Newcomb, N.Y.

Appalachians

Briceville, Tenn.	Pikeville, Tenn.	Delaware Water Gap, Pa.
Monterey, W.Va.	Fort Payne, Ala.	Estillville, Ky.
Franklin, W.Va.	Maynardville, Tenn.	Hazelton, Pa.

Basin Ranges

Fish Springs, Utah	Alturas, Cal.	Needles, Ariz.
Granite Range, Nev.	Long Valley, Nev.	

Coast Ranges

Coos Bay, Oreg.	Tamalpais, Cal.	San Francisco. Cal.

Mature Mountains

Delaware Water Gap, Pa.	West Point, N.Y.	Springfield, Mass.
Becket, Mass.	Lykens, Pa.	Boothbay, Me.
New Haven, Conn.	Charlestown, R.I.	New London, Conn.
Stonington, Conn.	Newcomb, N.Y.	Elizabethtown, N.Y.

Mountain Ridges

Antietam, Md.	Monterey, Va.	Fort Payne, Ala.
Estillville, Ky.	Franklin, W.Va.	Maynardville, Tenn.
Hazelton, Pa.	Lykens, Pa.	

Never Glaciated Mountains

Mt. Mitchell, N.C.	Needles, Ariz.	Cucamonga, Cal.

New England Mountains

Mt. Washington, N.H.	Becket, Mass.	Monadnock, N.H.
Hartford, Conn.	New Haven, Conn.	Charlestown, R.I.

Old Mountains, Peneplains, and Monadnocks

Monadnock, N.H.	Boston Bay, Mass.	Farmville, Va.
Atlanta, Ga.	Wausau, Wis.	Marathon, Wis.

Rocky Mountains

Sawtooth, Idaho	Pike's Peak, Colo.	Chief Mountain, Mont.
Marias Pass, Mont.	Livingston, Mont.	Huerfano Park, Colo.

Sierra Nevada

Sierraville, Cal.	Yosemite Valley, Cal.	Bishop, Cal.

Young Mountains

Alturas, Cal.	Pike's Peak, Colo.	Telluride, Colo.
Platte Canyon, Colo.	Huerfano Park, Colo.	San Francisco, Cal.
Shasta, Cal.	Sierraville, Cal.	Coos Bay, Oreg.

CHAPTER XVI

RELIEF FEATURES OF THE EARTH

Relation to Previous Topics

The forms of the land have in the previous chapters been considered topically and in some detail. It is intended in this chapter to study them in broad review, to consider them in their general relation one to another, and to inquire into the underlying causes for the earth relief.

The Oblate Form

The gravitational form of the sphere, by which the earth materials are arranged symmetrically around a centre, is disturbed by the centrifugal force resulting from rotation. This causes a slight flattening at the poles and a slight bulging in the equatorial belt, producing the oblate spheroid form, in which the polar diameter is 7899 miles and the equatorial diameter 7926 miles, a total difference of about 27 miles. Therefore from the pole to the equator there is a gradual increase in distance from the centre until the maximum of $13\frac{1}{2}$ miles is reached.

This bulging is plainly due to rotation, and if the axis of rotation should move, the position of the bulge would change; or, if the rate of rotation should increase or decrease, the amount of bulging would vary. This would happen because the main bulk of the earth is in a state of flowage, only the outer portion being rigid rock. Whether the earth's interior is molten, or merely plastic under the overlying load, adjustment would necessarily follow any change in rate or direction of rotation. Adjustment has been reached in relation to the present rate of rotation and to the present position of the axis, giving the degree of oblateness that characterizes the earth.

The oblate form is an important feature in the relief of the earth, being, in fact, the greatest known departure from the spherical form of the earth. It is so widely spread over the whole earth that the departure from the true sphere is not visible, and the land surface and ocean water alike conform to it.

Ocean Basins

Ocean Basins and Epicontinental Seas. — Approximately three-fourths of the earth's surface lies below the mean sea level and is, therefore, covered by ocean water. The total area of the earth's surface is about 196,940,000 square miles, while the area of the oceans is about 141,486,000 square miles. The greater part of this depressed area is in the form of a basin of irregular boundary, but the basin area is nearly 10,000,000 square miles less than the ocean area, for the ocean water overflows the edges of the continents throughout most of their extent. There the ocean water is shallow, in what have been called the *epicontinental seas*, but elsewhere the ocean basins are deep. The average depth of the ocean is from 12,000 to 13,000 feet, but, if the epicontinental seas were excluded, the average would be considerably greater.

The Continental Slope. — The ocean basins, exclusive of the continent fringe overflowed by the ocean water, are, on the average, steeply bounded by a slope, known as the *continental slope.* This sometimes rises above the sea, as along mountainous coasts like the Andes; but much more commonly it rises beneath the sea and terminates in a submerged platform, known as the *continental shelf*, which varies in width from a fraction of a mile up to several hundred miles. It is, therefore, not visible and is not commonly represented on maps. If there were no ocean waters to obscure the relief of the globe, there would be revealed a great area of depression of very irregular form, terminating in the steep continental slope. This borders the continental plateaus, only a portion of which now rise above sea level.

The Ocean Bottom Plain. — On the whole the ocean basins form a vast plain of gentle slopes, excepting at the margins, where the continental slope rises more or less irregularly. Here and there local elevations occur, sometimes rising above the sea level. These elevations are either (1) broad upward swells of the sea bottom, or (2) faulted and tilted blocks, or (3) volcanic cones. Frequently these are in combination. There are also areas of unusual depression, sometimes broad, moderately sloping basins, sometimes troughs. Ocean depths are discussed later (Chap. XIX).

Deposition the Prevailing Process. — These elevations and depressions, as well as the ocean basins themselves, are due to the operation of those forces which obtain their energy from conditions within the earth. The phenomena of denudation, by which the land surfaces are being diversified, are practically excluded from the area covered by the ocean waters, excepting at and near the shore line. Instead, the ocean bed becomes the seat of deposit from the denudation of the lands, either directly by the deposit of sediment, or indirectly by the deposit of organic remains, whose hard parts are mineral matter mainly derived from the land and distributed in the ocean waters in solution. This deposit tends to render the sea floor still more regular. In this respect the ocean basin topography presents a striking contrast to that of the denuded lands. Erosion on the continents produces pleasing irregularity, while deposition on the floor of the sea causes monotonous simplicity in topography.

Continental Plateaus

Area and Height of Continents. — Reckoned from the ocean borders, the land areas occupy about one-fourth of the earth's surface, or somewhat over 55,000,000 square miles; but if the submerged continent edge is included, the total area of the continental plateaus is something like 10,000,000 square miles greater, and if the sea level should sink about 600 feet approximately, this amount would be added to the land area. While the ocean basins average 12,000 to 13,000 feet in depth, the continents rise only about 2300 feet above sea level on the average. The mean lithosphere level is, therefore, well below the level of the ocean, lying at a depth of about 7500 feet. That is to say, if all the continent platforms were planed off down to this level, they would fill the ocean basins up to within 7500 feet of the present sea level. The ocean would then spread over the entire earth with a depth of over $1\frac{1}{2}$ miles, being 7500 feet plus the amount of water displaced by filling the ocean basins.

The Maximum Relief. — The average departure of the earth's surface from mean lithosphere level is nearly 10,000 feet on the continent side, and about 5000 feet on the ocean basin side, and the larger portion of this departure is on the continental slope, which is really the most prominent diversity in the relief of the globe, though in the main hidden from view by the ocean water. Usually this slope, entirely beneath the sea, has a vertical relief of from 10,000 to 15,000 feet; but in some places where it is extended above the sea in lofty mountain chains, it is much higher. Thus along western South America it is approximately 40,000 feet from the ocean bottom to the highest Andean peak in a distance of about 75 miles. This is probably the greatest relief feature on the earth within a limited area.

The maximum relief of the land above sea level is 29,002 feet in Mount Everest in the Himalayas, and since the maximum depth of the sea is 32,114 feet, the total relief is 61,116 feet, or about $11\frac{1}{2}$ miles, a little less than the difference between polar flattening and equatorial protuberance. This is about $\frac{1}{350}$ of the earth's radius, and, therefore, an exceedingly small amount as compared to the earth as a whole.

Continents Rougher than Ocean Basins. — As in the ocean basins, the most characteristic topographic form of the land is the plain, though there is a smaller proportion of plains on the land than in the ocean, and on the whole the plains on the land are rougher than in the sea. There are also extensive plateaus, broad upward swells of parts of continent area, faulted and tilted blocks, and volcanoes, as in the ocean. But on the continents denudation is, and has been, active; and deposition, while in progress locally, has no such widespread importance as in the sea. The lands, therefore, are greatly sculptured, uplifted portions of the earth are dissected into rugged form, and even lowlands present irregularities due to denudation.

Comparisons and Contrasts with Ocean Basins. — In their main features, therefore, ocean basins and continent platforms present both resemblances and differences. They resemble each other in the presence of forms due to vulcanism and diastrophism; but they differ (1) in the relative effects of denudation, and (2) in the fact that the one area is prevailingly elevated, the other depressed, the two areas being separated by the pronounced continental slope. The causes for the denudation and for the different effects in land and sea are readily understood, and have already been presented in detail in the preceding chapters; but the causes for the diastrophism and vulcanism by which the ocean basins, continental slope, continental plateau, mountain and plateau uplifts, and volcanic phenomena have been brought into existence are far less easy to interpret. These various phenomena are evidently allied in origin.

Changes of Level

Effect of Diastrophism, Vulcanism, and Other Movements. — Another phenomenon related in cause to those just mentioned is that of relative change of level of land and sea. This, as we have already seen, has in the past brought about great changes in the outline of the contact of land and sea, and in the level of parts of the land with reference to sea level. Also, changes of this nature are still in progress. Some of these changes are surely related to mountain uplift, others to vulcanism, and probably still others are related to slower, more widespread, movements of the crust, either rising or sinking of the land, or changes in the level of the sea floor. If the ocean bottom should subside an average amount of a hundred feet, the water would be withdrawn from vast tracts of sea bottom in the epicontinental seas; if it should rise a like amount, vast tracts of low land on the continents would be flooded by rise of the ocean waters. Similar results would be brought about by elevation of the continent plateaus or by their depression.

Effect of Withdrawal of Water. — While it is probable that most of the changes in relative level of land and sea are the outcome of some actual movements of the earth's crust, it is to be remembered that there may be actual changes in the amount of water. For example, water locked up in the earth's crust in the processes of weathering is removed from the sea; so is water locked up in snow and glaciers. On the other hand, water thrown out of volcanoes is added to the seas. If any cause were operating to change the rate of rotation, or the direction of the axis of rotation, this too would cause a partial redistribution of the liquid hydrosphere to conform to the changed conditions.

Although there are three other possible causes for some of the phenomena included under change of level, it is generally believed that they are in the main the result of actual changes in crust level, either operating directly to raise or lower the lithosphere, or indirectly by raising or lowering the level of the ocean as a result of changes in the submarine portion of the lithosphere surface.

Distribution of Oceans and Continents

Land and Water Hemispheres. — Speaking generally, the land areas of the globe are massed in the northern hemisphere, and the water areas in the southern. There is more than twice as much land in the former as in the latter. An even more striking division may be

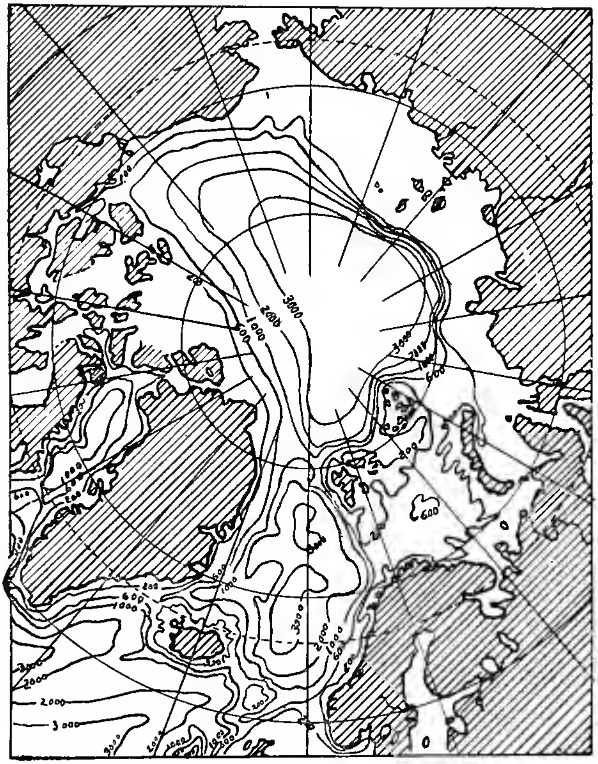


Fig. 379. — Map of the North Polar basin. Depths in metres. (de Martonne.)

made by dividing the earth into the so-called land and water hemispheres. The land hemisphere includes about six-sevenths of the land of the globe, but still more than half of its surface is water. In the water hemisphere only about one-fifth of the surface is land.

The North Polar Basin. — Surrounding the North Pole is a deep polar basin, whose area and extent are not known, but in which deep water was found to exist by Nansen and later by Peary (Fig. 379). This basin is fringed by a continental slope and then by a broad continental shelf, above which a number of islands rise. The continental shelf and islands almost cut off the polar basin from the rest of the oceanic areas, and even the Arctic Ocean itself, including the shallow parts which overflow the continental shelf, has but slight connection with the other oceans. It is almost cut off from the Pacific Ocean, being connected only by the shallow Bering Strait, only 50 miles wide. The connection with the Atlantic is more open, though if the sea bed were raised 600 feet, there would be only narrow straits here. The Arctic Ocean is, therefore, a nearly enclosed sea, really a bay-like prolongation of the Atlantic Ocean, with a deep circumpolar basin.

The New World Continental Plateau. — From the continental slope which surrounds the north polar basin, there extend two land masses, the smaller forming the New World, the larger the Old World. The New World area, starting with maximum breadth in the polar portion, narrows southward toward the tropics, giving a triangular form to North America. Connected by the Isthmus of Panama, and partly connected by the Antilles, is another triangular land mass, also tapering to the south. This pair of connected, triangular land areas stretches through 135° of latitude, forming the largest north-south extent of land on the globe. It terminates in the islands at the southern tip of South America.

The Old World Continental Plateau. — The Old World continental plateau has an entirely different form. It is, in the first place, broader where it commences in the circumpolar region, and it broadens greatly to form the huge Eurasian continent. Separated only by inland seas, the Mediterranean and Red, it extends into the African continent, which, broad in the north, tapers southward, giving the triangular form of Africa, which ends in a blunter point than South America and some 20° farther north. Elsewhere along the southern border, the Old World continental plateau terminates in peninsulas, like Arabia, India, and Indo-China. Toward the southeast it is fringed by island chains, and a maze of these partly connect it with the island continent of Australia. Although separated by straits, some of them very deep, Australia is essentially a part of the great Eurasian continental plateau.

The South-pointing Continents. — There is, in fact, with slight breaks, continuous continental plateau from southern South America through Eurasia to the southern tip of Africa, and to the southern tip of Australia, and to the eastern tip of Asia. The only breaks in this continental plateau, seemingly greater than they are because the ocean water covers the continental shelfs, are (1) the polar basin, and its narrow outlets, (2) the Mediterranean and Red seas, and (3) the greatest break of all, the series of inter-island channels between southern Asia and Australia. It may practically be said, therefore, that the continental plateau areas are massed around a basin in the north polar region, and that they extend thence southward, reaching farthest along three tongues, two of which are notably triangular in form.

The South Polar Continent. — With the oceanic areas the conditions are almost exactly opposite. There is around the South Pole a land area, called Antarctica, or sometimes the Antarctic Continent, instead of a circumpolar basin. It is completely separated from all the lands, being most nearly connected with South America.

The North-pointing Ocean Basins. — Around the Antarctic land mass extends a continuous sheet of water, there being prevailingly deep ocean basins outside the continental shelf that fringes Antarctica. From the Antarctic Sea, the ocean basins extend northward in three great tongues, the smallest being the Indian Ocean, between Africa and the Australian prolongation of Eurasia. The largest is the Pacific, which extends northward to the point where North America and Eurasia nearly join. Intermediate in size is the Atlantic, an hour-glass-shaped body, narrowed in the equatorial region, and broadening again in the North Atlantic. It terminates northward in the roughly circular northern sea, the partly cut off Arctic Ocean.

Islands within the Ocean Basins. — In all these oceans are islands and island groups, some small and single, more small and in chains, and some, like New Zealand, of large size. All are either (1) the crests of mountains rising above the sea, or (2) volcanic cones rising above sea level, or (3) coral islands built on volcanic cones or mountain peaks. These islands are present in the Atlantic Ocean and in the eastern Pacific; they are most numerous in the western Pacific and the Indian oceans. With the exception of those that fringe the continental plateau, they are all to be classed as phenomena of the ocean basins, not of the continents; they are local elevations in the great terrestrial depressions.

Continent Form

Three of the continents, North America, South America, and Africa, are triangular in outline, with the broadest part in the north. Eurasia is far more irregular, and Australia is a large irregular island.

Continent	North–South Dimension in Miles	East–West Dimension in Miles	Area in Square Miles
Africa	4550	4950	11,403,000
South America	4600	3150	7,598,000
North America	5100	4000	8,559,000
Europe	2500	3400	3,796,000
Asia	5350	6000	16,770,000
Australia	1050	2360	2,974,000
Antarctica	3475	——	5,122,000

Africa

Regular Coast of Africa. — The coast lines of Africa are notably regular, with no pronounced peninsulas or extensive fringing island chains, and consequently with an absence of enclosed seas. Omitting

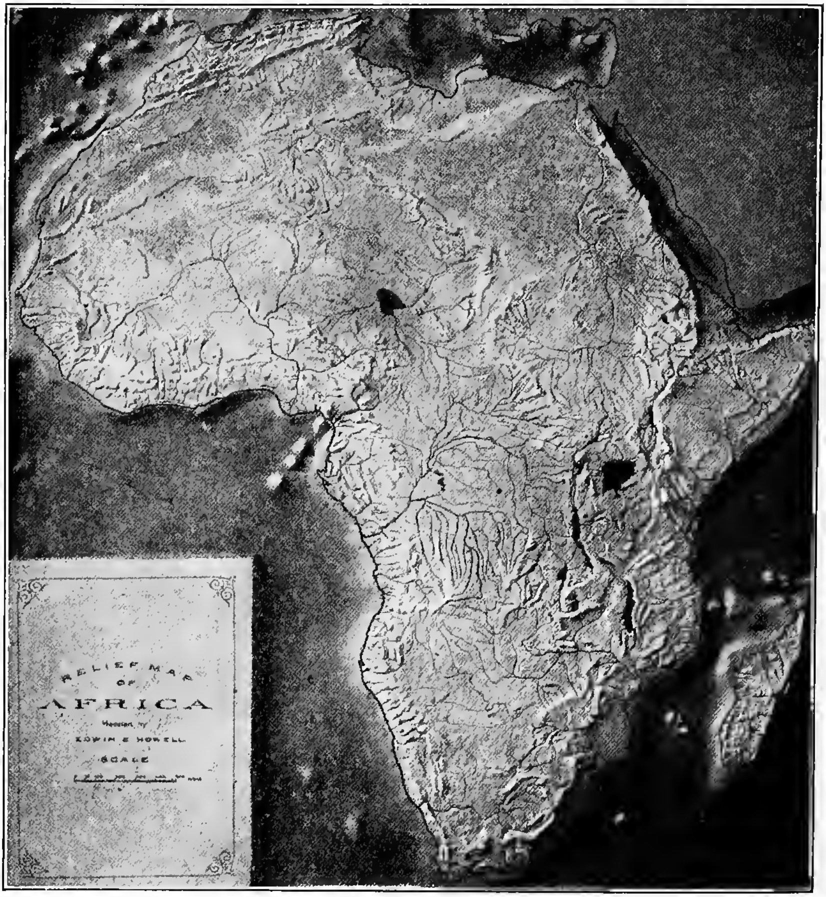


Fig. 380. — Model of Africa.

the Mediterranean and Red seas, which lie between Africa and Eurasia, the most notable indentation is the broadly open Gulf of Guinea. The largest projections are the Tunis Peninsula, where the Atlas Mountains extend into the Mediterranean, and the Somali Peninsula, which projects south of Arabia. Offshore there are some small island chains, like the Canary and Cape Verde islands, some individual small islands and island clusters, and a single large island, Madagascar, separated from the continent by the broad, deep Mozambique Channel (Fig. 380).

A narrow continental shelf fringes the continent, varying in width up to 50 or 100 miles, and beyond this the continental slope descends to the deep sea basin. With the exception of the eastern Atlas Mountains there is no mountainous peninsula projecting into the sea, and there has been no general subsidence of any part of the coast, causing an irregular, drowned coast line. There is, therefore, a general scarcity of harbours, though here and there is one due to local causes.

The African Plateaus. — The greater part of Africa is a plateau, descending rather abruptly along or near the coast to a narrow fringing coastal plain which merges into the continental shelf and which is delta land opposite the mouths of the river like the Zambezi, Nile, Niger, and Congo. In places the plateau edges are upturned, and there are mountainous areas back of the coast. Along the northern coast is the extensive chain of the Atlas Mountains, reaching a height of over 14,000 feet in the western half; in South Africa are the almost insignificant Cape Mountains, and in eastern central Africa are ill-defined mountains with numerous volcanic cones.

The highest of these are Ruwenzori (16,815 feet), Kenia (19,199 feet), and Kilimanjaro (19,717 feet). In this region is Kirunga, an active volcano, 700 miles from the ocean.

Rivers of Africa. — In descending from the interior upland the largest African streams are all interrupted by falls or rapids, the Zambezi by Victoria Falls, the Nile by the Cataracts, the Congo by the falls at Leopoldville, and the Niger by several rapids. These rapids and falls, and associated gorge sections, show clearly the topography of the drainage systems, and, therefore, testify to the fact that the present condition of the African plateau has not been of long duration. The interference with vegetation by the rapids and falls, together with the damp coastal lowlands of the tropical zone, and the desert areas in the southern and northern parts of the continent have seriously interfered with the exploration and occupation of Africa by white men. Largely for these reasons less is known about the physiography of Africa than any other continent.

River	Length in Miles	Area of Basin Square Miles	Ocean
Congo	2,900	1,200,000	Atlantic
Niger	2,600	563,300	Atlantic
Nile	3,400	1,273,000	Atlantic
Zambezi . . .	1,500	600,000	Indian

South America

Simple Outline of Continent. — In outline South America is almost as simple and regular as Africa. There are no pronounced peninsulas, the coast is prevailingly regular, especially the west coast, and there are no prominent, fringing island groups. Consequently there are no large, enclosed seas or bays. The largest peninsula is in Colombia, where a spur of the Andes projects into the Caribbean Sea; and another spur projects as the Isthmus of Panama. Aside from the Caribbean Sea, — enclosed between South America, southern North America, and the Antilles, — and the Gulf of Panama, — between the curving isthmus and the Columbian coast, — there are no other bays than small ones like the Gulf of Venezuela, the La Plata estuary, etc.

Along the northern coast there are numerous small indentations, for this is a mountainous coast, in which crustal movements are still taking place; indeed, there is essential continuity from the easternmost spur of the Andes along the Venezuelan coast to the Antillean chain. There are also numerous small bays and harbours along the lower, eastern coast. In southern South America the coast becomes exceedingly irregular. On the low-lying eastern coast there are several broadly open bays; on the mountainous western side is a system of fiords and fringing islands and channelways, like the coast of British Columbia and Alaska. In this intricate coast line glacial erosion has been a factor, and perhaps the chief one, in the development of the irregular coast line (Fig. 381).

Although South America terminates in the curving point of Patagonia, which ends in the island of Tierra del Fuego, the continent platform really extends several hundred miles to the east here, and includes the Falkland Islands, which rise, not from the deep sea, but from the continental shelf. From this broad part the continental shelf extends along the east coast with a width of over 100 miles for most of the distance to the Antilles, excepting in that part of Brazil which projects farthest east. On the west coast there is also a broad continental shelf off the coast of southern Chile, from which the numerous islands rise, but north of this the Andean coast is fringed by only a very narrow coastal plain at best. An uplift of 600 feet would very materially alter and extend the eastern side of South America, but would notably alter the western side only in the southern portion.

The Andes. — The main element of relief in South America is the Andean chain, which reaches its culminating height in Aconcagua, 22,860 feet, though rising to heights of 18,000 to 20,000 feet in other volcanic peaks, such as Chimborazo, 20,498 feet; and Cotopaxi, 19,613 feet. This vast mountain system extends from the southern tip of South America the whole length of the continent, consisting in the main of two parallel chains with an intermediate plateau, but with various minor ranges and interruptions. The mountain belt is narrowest and lowest in the south; it is broadest in the central or Bolivian portion, and in the north, where it frays out and spreads apart, as already stated, one prominent division extending into the Isthmus of Panama, one northeastward in the Antillean chain. On the western

FIG. 381. — Model of South America.

face the descent to the narrow, fringing coastal plain is steep, and, excepting in the southern portion, the mountain face is remarkably regular, though in broad sweeping curves. The eastern face is less regular, but is also steep. As we have seen (p. 425), this great mountain system is still in process of growth; earthquakes are frequent and violent, and volcanoes are active.

Highlands of Guiana and Brazil. — There is a mountainous highland in the north of South America, known as the Guiana or Venezuelan Highland, which is said to reach an elevation of 11,000 feet. A third highland occupies eastern Brazil and is known as the Brazilian Highland. It is a denuded mountain and plateau region of ancient origin and has a general elevation of from 2000 to 3500 feet, attaining an altitude of 9000 to 10,000 feet in the peak of Itatiaia in the south.

South American Plains. — Between these three highland regions is an extensive area of plains, made of sediments worn from the bordering mountains and mainly deposited in the ocean during a former, lower stand of the land. The plain is continuous from the pampas of southern South America, where it extends from the eastern base of the Andes to the sea, northward to the mouth of the Orinoco River. It narrows between the Brazilian Highlands and the Andes, but broadens farther north, and there, in the Amazon valley, extends from the Andes to the Atlantic. These plains, connecting the highlands from which their sediments were derived, give continuity to the land by binding the parts of the mountain skeleton together.

Drainage of South America. — The drainage of South America is determined by the highland areas. Only short streams descend the Andes toward the west, though some of these in the south head on the eastern side of the mountains. Other streams flow eastward to join the Orinoco, Amazon, and Parana drainage, and a few flow straight to the ocean in Argentina, and northward to the Caribbean in Colombia and Venezuela. The Guiana Highland drains primarily northward into the Orinoco and southward into the Amazon, while the Brazilian Highland has a radiating system of streams, some flowing independently to the sea, but the majority entering the Parana or the Amazon.

Besides the numerous smaller streams there are three great rivers flowing across the plains, the Parana southward, the Amazon and Orinoco eastward. With numerous tributaries fed from mountain regions, in a climate of abundant rainfall, these three rivers have large volume; and since they flow over broad, level plains, not greatly elevated above sea level, they have primarily moderate slope, and are, therefore, useful for navigation. Unfortunately they lie mainly in the tropical zone, a region of unhealthfulness and sparse settlement, so that their usefulness is thereby diminished, the lower Parana which lies in the temperate zone being less influenced in this respect than the others.

River	Length in Miles	Area of Basin Square Miles	Ocean
Amazon	3,300	2,500,000	Atlantic
Orinoco	1,350	366,000	Atlantic
Parana-Plata	2,580	1,200,000	Atlantic
São Francisco	1,800	200,000	Atlantic

North America

Western Coast. — In outline North America is far more irregular than either Africa or South America. Like them it has a general triangular shape, but it departs from this simple form very materially.

In the northwest is the great projection of Alaska, bordered by a broad continental shelf which extends under Bering Sea to Asia and northward into the Arctic. Along this shelf the continental plateau is connected with that of Asia, and only a moderate uplift would unite the two continents by a broad lowland several hundred miles in width. From Alaska the narrow Alaska Peninsula extends southwestward and is continued by a narrow, submarine mountain ridge, upon which rise a number of volcanic islands with numerous active and extinct cones. These islands, the Aleutian, form the southern boundary of the shallow Bering Sea.

Southeastward from Alaska down to the narrowest part of the continent in the Isthmus of Panama, the coast is moderately regular on the whole, though with several broad curves. The regularity is broken in the north, where the sea occupies mountain valleys which have been profoundly deepened and broadened by glacial erosion. Here for a thousand miles a vessel may sail along the famous Inside Passage, shut out from the ocean by a maze of islands. The regularity is also broken by the long, narrow peninsula of Lower California, which encloses the deep, narrow Gulf of California. It is a southern spur of the Coast Ranges.

This entire coast, from Panama to the Aleutian Islands, is mountainous, and throughout much of the distance there has been recent uplift, and in places, as near Mount St. Elias and near San Francisco, crustal movements are still in progress. This coast resembles that of western South America in rising out of deep water for most of the distance, with only narrow strips of coastal plain and continental shelf here and there.

Northern and Eastern Coast. — The northern coast of North America is low and irregular. Much of it is a worn-down mountain region of low relief, which, by subsidence, has been partly drowned, forming numerous straits and bays, of which the largest is the shallow Hudson Bay. The highest parts of this old land rise as islands and peninsulas, the largest of the islands being Baffin Land, and the largest peninsula Labrador. These islands and peninsulas rise above a broad continental shelf, which stretches northward to the deep polar basin. Greenland is essentially a part of this continental plateau, being really a part of it in the north, but in Baffin Bay being separated by a deep basin. If the land were uplifted, so as to raise this broad northern continental shelf above the sea, there would still be a long, deep bay between Baffin Land and Greenland, which would then be a peninsula projecting southward from the northern part of the continent (Fig. 382).

The irregular, submerged coast of the old mountain land extends southward along the east coast to New York. Here also the coast is

Fig. 382. — Model of North America.

very irregular with numerous bays, peninsulas, and islands, the largest being the Gulf of St. Lawrence, the peninsula of Nova Scotia, and the island of Newfoundland. There is also a broad, fringing continental shelf, attaining greatest breadth southeast of Newfoundland, where lie the shallow Fishing Banks of Newfoundland.

Southward from New York to Honduras there is a fringing coastal plain, attaining special breadth in Florida and Yucatan, two projecting peninsulas which rise as plateaus out of the sea, but with only a part of their size revealed because of the bordering continental shelf now covered by shallow water. This coastal plain is low and only recently raised above the sea, though now somewhat irregular by a still more recent subsidence, giving rise to shallow bays at the stream mouths.

Antillean Region. — Between southern United States and South America the conditions are more complex. The two continents are connected by the narrow irregular mountainous land of Central America. They are also nearly connected by the Antillean chain, a great mountain range rising from the deep ocean floor. Between this chain and the mainland of North and South America are the two partly enclosed seas, the Gulf of Mexico and the Caribbean Sea, shut in not only by the visible land, but even more so by a submerged mountain ridge, which is broken across by only two or three deep passages.

The Antillean chain, which is continuous with the Andes of northern South America, sweeps in a great bend along the lesser Antilles and through Porto Rico and Haiti, where it splits into three parts. The northernmost, plateau-like, extends through the Bahamas and the shallow banks on which they lie, and, with only a narrow break, to the Florida plateau. The southernmost extends from the western point of Haiti through Jamaica and along a broad submarine ridge to the point of Honduras. The central branch extends through Cuba nearly to the Yucatan plateau; but a submarine range also extends westward from southern Cuba. This branching mountain range, together with the peninsula of Yucatan, serves to so divide the great inland sea as to lead to its having the two separate names of Gulf of Mexico and Caribbean Sea.

North American Cordillera. — North America, like South America, has its main mountain area in the west, but the mountain belt is far broader and more complex. The North American Cordillera is continuous from southern Mexico to northern Alaska, and westward through the Aleutian Islands. The Rocky Mountains, varying in character and given different names, are traceable from northern Mexico to western Alaska. West of these mountains is a broad plateau area, mountainous in places, also traceable from southern Mexico to northern Alaska. The Pacific Mountains fringe the coast continuously from the southern part of Mexico to the Aleutian chain. Throughout this belt there has been uplift of recent date, and throughout it is a region of recent volcanic activity; but only at the northern and southern ends is it at present a region of active volcanoes. The culminating point in this mountain belt is Mount McKinley in Alaska, 20,464 feet; but the volcano Orizaba in Mexico is 18,314 feet; Pike's Peak in the Rockies is 14,111 feet; Mount Whitney in the Sierra Nevada is 14,502 feet; and there are many other peaks above 10,000 feet.

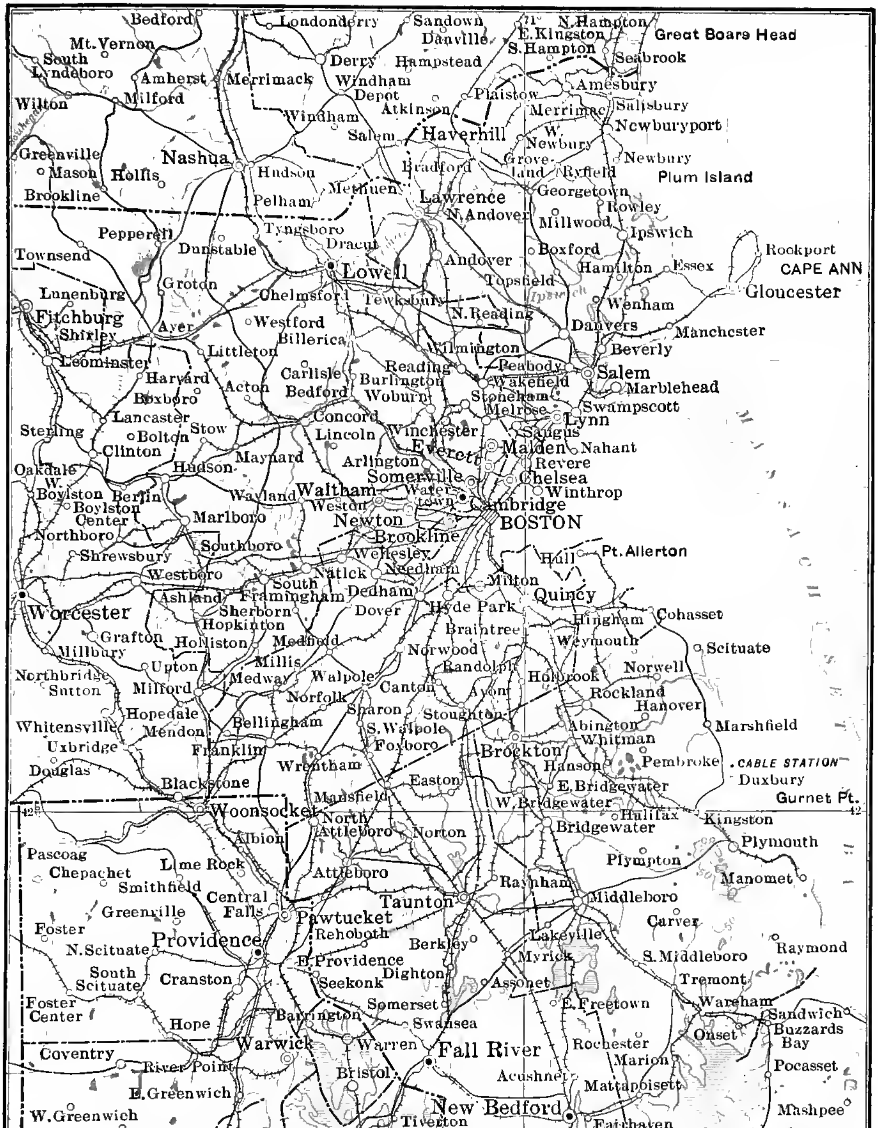
In Central America there is a complex of mountains, apparently more related to the Antillean chain than to the Andes or the mountains of western North America. In this mountain section, as in the Antilles, evidence of recent growth is abundant, and active volcanic cones are numerous. The Central American Mountains attain elevations of 12,000 to 13,000 feet. The Antillean Mountains rise from an ocean platform, 15,000 feet or more below sea level, and rise in Cuba to 8600 feet in Pico del Turquino. These mountains, therefore, rise fully 25,000 feet above their base beneath the sea, and even more if reckoned from the Blake Deep near Porto Rico, which is 27,360 feet, while Mount Yunque in Porto Rico is 3609 feet, and Lowa Tina in Haiti, not far distant, is 10,300 feet, or 37,660 feet above the sea bottom of the Blake Deep.

Appalachian and Laurentian Highlands. — Compared to the western mountains, the Appalachian system is both small and low. It extends northward from Alabama through New England, Nova Scotia, and Newfoundland, being ordinarily no more than 2000 or 3000 feet in elevation, though rising to a height of 6711 feet in Mount Mitchell in North Carolina, and 6279 feet in Mount Washington in New Hampshire. These mountains are old and much-denuded, and in this respect contrast also with the western mountains.

The ancient Canadian mountains, or Laurentian Highlands, now worn to a plateau of low relief, attain considerable elevation in only one part, namely, in northern Labrador. Here are the highest mountains of eastern North America, but their exact elevation is unknown.

Plains of North America. — Between the Appalachian and Rocky mountains and northward to the Laurentian Highlands are broad plains which also fringe the eastern Rocky Mountains northward to the Arctic. Coastal plains border the eastern and southern coasts, and a broad plateau lies between the Rocky and Pacific mountain chains.

Drainage Features. — The chief drainage is determined by the four great features of the continent: (1) the eastern mountains, (2) the western mountains, (3) the Laurentian Highlands, and (4) the intervening plains. The St. Lawrence system lies essentially along the southern boundary of the Laurentian Highlands, though crossing spurs of it in the extreme west, and north of New York. It enters the sea by crossing the northern Appalachian system. Aside from the tributaries to the St. Lawrence, the Laurentian Highlands shed their waters mainly northward through a large number of lake-interrupted streams, none of which are of much importance because flowing through a country of sparse population into a region of even less value.



WILLIAMS ENGRAVING CO., N.Y.

BOSTON AND VICINITY

Part of the peneplain of southern New England, showing the harbours of Boston, Fall River, New Bedford, and adjacent cities, and the dense railway and street-car net of a long-settled industrial region in eastern United States. Contour intervals 50 and 100 meters. (From Boston Sheet, North K 19, International Map of the World on the scale of 1 : 1,000,000.)

The Appalachian Mountains shed water eastward by numerous short streams and westward to the Mississippi, which drains by far the greater portion of the interior plains. The Rockies also shed water to the Mississippi in their central portion; in the south by smaller, shorter streams in Mexico directly to the sea, and farther north to the Rio Grande. In Canada water flows from the mountains eastward to the Mackenzie and to the Saskatchewan-Nelson. From the Rocky Mountain divide two large streams flow westward to the ocean, the Colorado and the Columbia, and numerous small streams flow into the Great Basin. In Mexico and Central America the streams are all short, and in Mexico there is a large area of interior drainage. Numerous streams from the mountains flow to the Pacific north of the Columbia, but the largest is the Yukon, which enters the Bering Sea arm of the Pacific.

Thus the drainage of North America is complex, and many of the streams are of little or no use for navigation. The two principal exceptions are the St. Lawrence and Mississippi systems, which lie in part in the great area of central plains.

River	Length in Miles	Area of Basin Square Miles	Ocean
Arkansas	2,170	185,671	Atlantic
Colorado	2,000	225,049	Pacific
Columbia	1,400	216,537	Pacific
Mackenzie	2,868	677,400	Arctic
Missouri	3,000	527,155	Atlantic
Missouri-Mississippi	4,300	1,257,000	Atlantic
Saskatchewan-Nelson	3,840	486,500	Atlantic
Ohio	975	201,720	Atlantic
Rio Grande	1,800	240,000	Atlantic
St. Lawrence	2,600	565,000	Atlantic
Yukon	2,300	330,000	Pacific

Eurasia

A Complex Mountainous Continent. — From every standpoint this is the most complex of the continents. Like the others it is roughly triangular in shape, but with the apex of the triangle in the west instead of in the south. It is the largest of the continents, the most mountainous, and the most irregular. The continents are so complex that it is very difficult to describe them in general terms.

Perhaps the most striking feature is the great complex of mountains, extending with little break from Spain to China. These mountains vary in height, in direction, and in characteristics, but in the main they are young, and throughout much of the distance they are at present rising, judging from the frequency of earthquake shocks.

Europe

Youthful Southern Mountains. — Spain is a somewhat broken plateau, bordered on one side by the Pyrenees, 11,168 feet, and their continuation, the Cantabrian Mountains, and, on the other, by the Sierra Nevada, 11,420 feet. East of these are the Alps, 15,781 feet with the Swiss plateau to the north, and the Jura Mountains, 5500 feet, on its other border. On the western end the Alps curve sharply and extend to the Apennines, which pass southward through Italy, forming the backbone of this peninsula, then curve into Sicily, and by a submarine ridge to the Atlas Mountains of Tunis. The Alps disappear in Austria, but continuous mountain ranges extend southeastward through the Balkan Peninsula to the islands south of Greece, and into Asia Minor. Other mountains sweep in a great curve around the northern and eastern sides of the Hungarian Plain. These mountains are known by different names in their several parts, one portion being the Carpathians. Farther east are the Caucasus.

These mountains are all young, many of them are still in process of uplift, and the depressions near them are in places still sinking. This is true especially of parts of the Mediterranean, a down-sunken part of the earth's crust developed in connection with the recent great mountain movements. This complex of mountains determines the main topographic features and outline of southern Europe. The peninsulas and islands are mountain areas, and, because of the irregularity of direction of the mountains, these land forms are also irregular. Valleys exist between the mountains and in the areas where the mountains curve, some filled with water like the Adriatic, others dry land like the Hungarian Plain and the Po valley, an extension of the Adriatic depression.

Older Western Mountains. — In southern Ireland, Belgium, Germany, and Austria, north of the Alps, is an ancient mountain range worn to low relief, and the seat of recent volcanic activity. A very extensive mountain system of still more ancient date extends from France, through the British Isles, and to the northern end of the Scandinavian Peninsula. This has also been much reduced since its period of formation, but is still fairly rugged in Scotland and in Scandinavia, in the former reaching an elevation of 4406 feet, in the latter 8400 feet.

European Plains. — Between the Scandinavian upland and the mountains of southern Europe is a great plain, broadening eastward where it extends into Asia. This plain is crossed by the low Ural Mountains, which extend 1500 miles, rising to a height of over 5000 feet in the north and south, but very low in the middle. The mountain axis of the Urals is continued northward in the islands of Nova Zembla.

Rivers. — Each peninsula of Europe has drainage of its own, but with this exception the drainage radiates mainly from two centres, one in the lofty Alps, the other in the low plains of central Russia. Some of the latter flow northward, others southward into the Black Sea, or into the Caspian as in the case of the Volga. The Alpine drainage finds its way southward in the Po, eastward in the Danube, northward in the Rhine, and southwestward in the Rhone. All these streams flow across extensive plains; and other well-known streams cross these plains, like the Elbe in Germany, and the streams of France, which radiate outward from the central highland. Because of their low grade, many of these streams are navigable.

River	Length in Miles	Area of Basin Square Miles	Ocean
Danube	1,770	300,000	Atlantic
Dnieper	1,200	242,000	Atlantic
Dwina	1,000	140,000	Arctic
Elbe	725	55,000	Atlantic
Po	400	27,000	Atlantic
Rhine	800	75,000	Atlantic
Rhone	500	38,000	Atlantic
Seine	482	30,300	Atlantic
Thames	228	6,100	Atlantic
Volga	2,400	563,300	Caspian Sea

Irregular Coast. — The coast line of Europe is one of extraordinary irregularity. Some of it is mountainous, especially in the south, and in the Scandinavian-Scottish mountain region; but much of it is low-lying, notably where the plain extends to the sea along the English Channel, North Sea, and Baltic Sea. In the Mediterranean the irregularity is due mainly to movements associated with mountain growth. Locally, as in Greece and along the eastern Adriatic coast, subsidence has produced a typical drowned coast. The Black Sea occupies a deep basin between the mountains of Asia Minor and the Caucasus and their eastern continuation in the Crimean Peninsula. The Caspian, really in Asia, occupies a basin on the border between the Caucasus and other mountains of western Asia, on the one side, and the great Eurasian plain on the other. Owing to the arid climate, it does not rise to the point of overflow, and its surface lies 85 feet below sea level.

The northern and western outline of Europe is determined mainly by subsidence. This is not true of the plateau peninsula of Spain nor of the Bay of Biscay, the latter occupying a deep basin between the Cantabrian Mountains and the coast of France, which here projects to form the peninsula of Brittany, the southernmost part of the Scandinavian-Scottish mountain system. From this point northward, and thence along the Arctic coast, the coastal features are mainly the result of subsidence. The edge of the continental plateau, as determined by the position of the continental slope, lies well outside of Brittany, Ireland, and Scandinavia. The British Isles rise from the continental shelf; the English Channel, North Sea, and Baltic are entirely on it; and north of Scandinavia and Russia it extends in a broad submerged shelf northward to the deep polar basin. The subsidence has given rise to great irregularity in detail, as in the estuary of the small river Thames and to the larger features of outline as well. The higher parts of the old mountain land rise to form the British Isles and Scandinavia, while the lower parts are submerged between Brittany and England, and between Scotland and Scandinavia. The submergence has also permitted the ocean waters to spread over a broad tract of lowland plain in the southern part of the North Sea and in the Baltic Sea, the two being separated by a higher part of the plain where the Danish islands lie, and the peninsula of Jutland projects northward, almost uniting with the low, much-denuded mountain land of southern Sweden. The fiords of Norway are due wholly or in part to glacial erosion.

The irregular coast line of Europe giving a multitude of harbours, and the enclosed seas penetrating far inland and offering both opportunity for learning navigation and providing routes to a wide tract of country, have been factors of high importance in the development of Europe. The plains have given basis for agriculture, the navigable rivers have served as highways, and the mountains, of varied height and direction, have served as protection. The physiography gives ample basis for the high development of Europe; it has had a powerful influence in guiding its history; and it offers explanation of the large number of diverse nationalities which now hold possession of it.

Relation to Adjacent Continents. — Europe cannot be separated from Asia by any natural dividing line; it is really a west-extending peninsula of Eurasia. Although completely separated from Africa by the Mediterranean, it is almost connected at the Strait of Gibraltar, is not far separated between Sicily and Tunis, and is only a little farther removed from Greece and Crete. The Mediterranean is really a huge basin in the great Eurasia-Africa continental plateau, similar on a larger scale to the Black Sea.

Europe is much more definitely separated from North America. The deep polar basin lies between them, but they are less separated farther south. A long, broad submarine ridge extends from Scotland to Iceland with the Faröe Islands rising about it; and Iceland is only slightly separated from Greenland, which, as we have seen, is really continuous with the North American continental plateau. Thus, if the continental slope is taken as the boundary of the continents instead of the present water margin, Europe and America are all but united. Even with the present distribution of water and land, it is but a series of short steps from Scotland to the Faröe Islands, to Iceland, to Greenland, and to Labrador. It was this shortest, easiest route that the Norsemen found in the first discovery of America.

ASIA

Central and Southern Mountains. — The mountains of southern Europe do not terminate in the Balkan Peninsula, but are continued on through Asia Minor and Persia. On the northern side are the Caucasus, really in Europe, with one peak, Mount Elbruz, 18,200 feet high, but in Asia Minor and Persia the mountains are much lower and less definite ranges, with intermediate valleys and plateaus. Mountain growth is still in progress in this region, and earthquakes are frequent and destructive, and there are numerous volcanic cones, at least one of which, Ararat, is to be classed as active. These mountains extend in various directions, but their general trend is eastward.

The great Arabian Peninsula is mainly a plateau, separated from the mountainous country of Persia and Asia Minor by a broad depression. This lowland is occupied in the lower portion by the Persian Gulf and in the upper by the plain of the Tigris and Euphrates rivers. Arabia in form and characteristics seems less related to Asia than to Africa, with which it is connected by the Isthmus of Suez and nearly connected at the Straits of Bab-el-Mandeb. Between the two lies the long, narrow, and deep Red Sea basin, which with moderate changes in the southern end would become transformed to a lake. This is probably a rift valley, the bottom of which has sunk, much as has been the case in the long, narrow trough extending out of its northern end and in which the Dead Sea lies.

East of Afghanistan and Bokhara comes a great complex of mountains. From a great mountain knot, the Pamir, called the "roof of the world," three main branches spread out, one the Tian Shan, or the Mountains of Heaven, extending eastward into Mongolia, another the Kuen Lun Mountains farther south, extending to China, and the two enclosing the East Turkestan Plateau or the Tarim Basin. Other mountains farther north border and extend into Mongolia. The third branch, the Himalayas, swing southeastward along northern India, and between these mountains and the Kuen Lun Mountains is the plateau of Tibet. This is the greatest mountain complex in the world and it includes the highest mountain peaks, — Everest in the Himalayas, 29,002 feet, and others approaching this elevation, — while between the spreading chains are the highest plateaus in the world — Tibet being 10,000–15,000 feet in elevation (Fig. 383).

South of the mountains of Afghanistan and the Himalayas is a broad lowland, occupied by the Indus, Ganges, and Brahmaputra rivers. This lowland is, without doubt, a depression associated with the mountain uplift to the north. Within it movement is evidently still in progress, for it is the seat of frequent destructive earthquakes. It has been filled and raised above sea level by the deposit of sediment brought by the rivers from the Himalayas, which, because of their youth, are high, rugged, and the seat of rapid denudation. On a large scale, this is analogous to the condition in the Po valley at the southern border of the Alps. South of the lowland is the triangular plateau of India, between which and Arabia lies the broad, deep Arabian Sea. Ceylon is essentially a part of India, being separated by shallow water; and off the west coast of India is a north-south submarine mountain chain, reaching south of the equator, and with numerous small island peaks rising above sea level.

In the east the mountains branch, their direction changes, and in place of east-west and northwest-southeast mountains there are

FIG. 383. — Model of Eurasia.

prevailing north-south and northeast-southwest mountains. A southward swing of the mountains east of the Himalayas gives rise to a series of north-south ranges in Indo-China, which, with India, encloses the broad, deep Gulf of Bengal. One branch of these mountains, extending through Burma, is continued to Sumatra by a submarine mountain ridge, on which a chain of small islands rises above sea level. Another branch extends down the Malay Peninsula, swinging eastward toward Borneo. The eastern lobe of the peninsula of Indo-

China is continued by a submarine plateau, which occupies all the space between Siam, Borneo, Java, and Sumatra.

Eastern Mountains and Volcanoes. — These mountains swing eastward through the East Indies and New Guinea, and beyond this, in the western Pacific, are several submarine mountain ridges, from many of which volcanic cones rise. Throughout this island belt, mountain growth is in active progress, earthquakes are frequent, and active volcanoes numerous. The mountains also swing northeastward through Borneo, the Philippines, Formosa, the Japanese Islands, and Kamchatka. This is also a growing mountain range, with frequent earthquakes and active volcanoes. It rises from the ocean floor at a depth of 15,000 to 20,000 feet, and in places more, and extends more than 10,000 feet above sea level in many places. In Java, for instance, there are peaks 12,000 feet in height, in the Philippine Islands, 10,000 feet, in Japan over 12,000 feet, and in New Guinea over 13,000 feet. Most of these lofty peaks are volcanic cones, like Fujiyama in Japan, which is 12,365 feet in elevation.

This fringing-island-mountain-chain encloses a succession of more or less oval basins, occupied by epicontinental seas — the South China Sea, the East China Sea, the Japan Sea, and the Okhotsk Sea, while still beyond lies the Bering Sea, also island-enclosed. The mainland coast is also mountainous in large part, and, in one place a mountainous peninsula projects. This Peninsula of Korea extends toward Japan, with which it is connected by a submarine plateau. It helps to enclose the Yellow Sea on the south and the Japan Sea on the north. The Japan Sea is enclosed on the south by the long island of Sakhalin, the crest of one fork of the Japanese mountain range, the other branch extending to the peninsula of Kamchatka by a submarine mountain ridge, from which the Kurile Islands rise.

The extraordinary irregularity of the Asiatic coast is thus, in the main, determined by mountain and plateau blocks with intermediate depressions. Some of the mountains are on the mainland, some project from the mainland along peninsulas, and some fringe the coast as submarine chains with island crests. These fringing islands are most numerous and occupy the broadest area in the south, where the ranges curve in a great lobe.

Siberian Plain. — Northern Asia is mainly a plain and a hilly region of low relief. This extends to the Arctic, where subsidence has given rise to an irregular coast, like that of Arctic Europe; and here, also, there is a broad continental shelf, as in the case of all Arctic lands. Most of the Asiatic coast is fringed by a continental shelf, varying greatly in width from place to place, and becoming especially broad in some of the enclosed seas and in the great mountain bend between Borneo, Sumatra, and the Malay Peninsula.

Features of the Asiatic Mountains. — The lobate form of some of the Asiatic mountains is a striking feature (Fig. 384.) Some of these lobes, like that just mentioned, are remarkable for their great size and for the extent of the curvature. Others, like the Himalayas, merely bow out in moderate curves. Similar lobation of mountain chains is a common phenomenon; for mountain chains rarely extend in straight lines, but have a curving outline, as in the Andes, the Pacific mountains of western North America, the Aleutian Islands, and many others. Also the recurving of mountains is a common phenomenon, as in the Alps, the Carpathians, and the northern Andes and West Indies. Still another noteworthy feature is the mountain knot like that of the Pamir, beyond which the mountains spread apart like a frayed rope, as the northern Andes and the Alaskan mountains do.

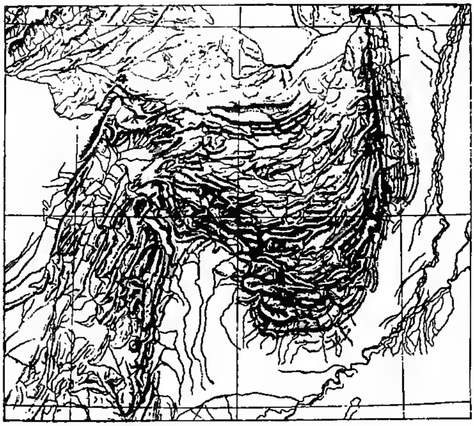


FIG. 384. — The arcuate plan of the mountains in part of India. (St. Martin and Schrader.)

The Asiatic mountains not only affect the continent outline and the land topography, but they produce important effects on the climate, and have had a dominating influence on the distribution of people.

Rivers of Asia. — The mountains also profoundly affect the drainage. A part of the drainage is into interior basins, especially in the central part, from the Caspian and Aral seas, both without outlets, to Mongolia and Tibet. In this basin region there are extensive deserts, like the Desert of Gobi and the great Tarim Basin. Some of the lakes, such as Lob Nor in the Tarim Basin, have had notable fluctuations in level, as was the case with Lakes Bonneville and Lahontan in the Great Basin of western United States. The abandoned beaches of these ancient lake levels in central Asia are well preserved. Towns have been abandoned because of the climatic oscillations which caused these changes in the lakes and rivers. From the peripheries of this area of interior drainage, water is shed outward in all directions: the Ob, Yenisei, and Lena northward to the Arctic; the Amur, Hoang-ho, and Yangste-kiang eastward to the fringing seas along the Pacific coast; the Mekong, Salwen, Brahmaputra, Ganges, and Indus southward to the seas branching from the Indian Ocean. Omitting the minor streams and those of the islands and peninsulas, the drainage of Asia is of very simple plan: it is radial from a great central highland area of mountain and plateau, within which there is interior basin drainage.

River	Length in Miles	Area of Basin Square Miles	Ocean
Amur	2,800	520,000	Pacific
Brahmaputra	1,800	425,000	Indian
Ganges	1,500	440,000	Indian
Hoang-ho	2,700	570,000	Pacific
Indus	1,800	372,700	Indian
Irawadi	1,500	158,000	Indian
Lena	2,800	950,000	Arctic
Mekong	2,800	280,000	Pacific
Ob	3,200	1,000,000	Arctic
Salwen	1,750	———	Indian
Yangtse-kiang	3,200	548,000	Pacific
Yenisei	3,000	1,500,000	Arctic

Australia and Oceania

Relation to Eurasia.—Australia, greatest of the islands south of Asia, presents no great complexity of topography. It is surrounded by a broad continental shelf, beyond which there is a steep descent to the ocean floor, excepting in the north, where there is prevailing shallowness through the East Indian region to Asia. Australia may, therefore, be considered as essentially a part of the great Eurasian continental plateau.

Regular Coast. — The coast line is moderately regular, though, along a large part of the coast, subsidence has given rise to a series of small bays and harbours. There is only one good-sized bay, the Gulf of Carpentaria in the north. Along the northeastern shore, for a thousand miles or so, is the Great Barrier Reef, the largest coral reef in the world, and between it and the coast is a shallow lagoon of variable breadth and depth. The only island of large size is Tasmania, rising from the continental shelf, and therefore essentially a part of the continent (Fig. 385).

Plateau of Australia. — Most of the interior of Australia is a desert plain and low plateau, with low, short mountain ranges, 1000 to 2000 feet high, as in the Great Basin of western United States. Like the Great Basin also a large part of Australia is a region of interior drainage. Short streams flow to the sea from the border of the interior desert, and one, the Darling, the largest in Australia, rises, together with its tributary, the Murray, in the eastern mountains and flows to the sea across the desert.

River	Length in Miles	Area of Basin Square Miles	Ocean
Cooper-Barcoo	800	———	Lake Eyre
Darling	1,100	———	Indian
Murray	1,000	270,000	Indian

Eastern Mountains. — The eastern mountains, the only notable mountain range in Australia, extend along the eastern coast, though separated from it by from 30 to 100 miles or more of low, hilly land and plains, fertile and well-watered. These mountains are neither lofty nor rugged, for they were raised at an earlier period and have long been denuded. They are not the seat either of vigorous earthquakes or

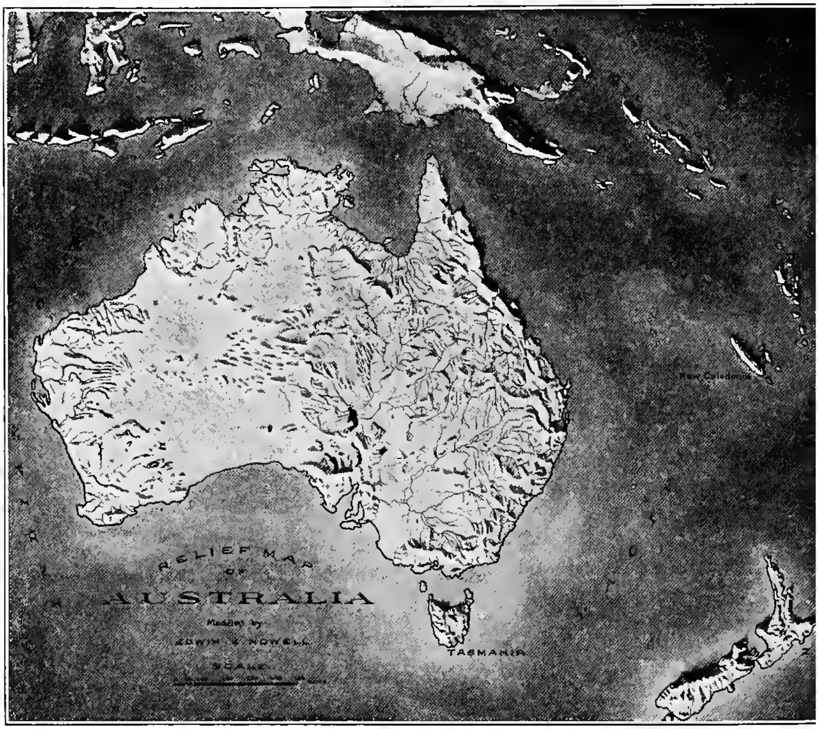


FIG. 385. — Model of Australia.

volcanic activity. They consist of a series of low, broken ranges, and the highest peak, Mount Kosciusko, rises only 7336 feet, and elsewhere the highest elevations commonly range between 4000 and 7000 feet.

New Zealand. — Twelve hundred miles east of southern Australia is the New Zealand mountain chain, severed by a submerged pass to form two large islands, each over 500 miles in length. This mountain range continues some distance on either end in a submarine ridge, and is possibly continuous toward the northeast with the ridge on which the Tonga and Friendly islands lie, and toward the northwest with the ridge from which Norfolk Island rises. Both the North and the South islands of New Zealand are mountainous, attaining an elevation of 12,349 feet in Mount Cook in the South Island, where the mountains rival the Alps in height and in grandeur. The mountains in the North Island are lower, but here there are numerous volcanic cones, two of them being active. This mountain chain is one of recent uplift and is still growing, for vigorous earthquakes are experienced, and, in the North Island, volcanic activity has not died out.

Islands of the Pacific. — The many islands in the Pacific east of Australia and Asia are mainly mountain crests or volcanic cones, rising from submarine mountain chains and often of considerable length. Others are isolated volcanic cones or groups of volcanoes, some reaching the surface only by the veneer of coral reef upon them.

Antarctica

Too little is known of this land mass to warrant more than the briefest mention of it. One cannot yet be certain that there is continuous land there, for it is possible that there is an archipelago of large islands united by a great ice cap. Such evidence as we have points toward the conclusion that it is really a land of continental proportions, with much lofty mountain topography, including Mt. Fridtjof Nansen, 15,000 feet. At the South Pole the ice plateau is about 10,700 feet high, and the mean altitude of the continent is approximately 6000 feet. There are at least two volcanoes, one, the active cone Erebus, rising about 12,365 feet. The continent has no rivers, all the drainage being glacial, the Ross Barrier having retreated 20 to 30 miles since 1839. The land is fringed by a broad, continental shelf, and there is geological reason for suspecting that, at some former period, Antarctica and South America may have been united. The coal deposits within 5° of the pole suggest vast changes of climate, such as would have taken place with a shifting of the earth's axis during the geological past.

References to Literature

See the bibliographies of the chapters on *Plains and Plateaus* (p. 521), *Mountains* (p. 578), *Shorelines* (p. 384), *The Ocean* (p. 665), etc. The best treatments of the relief features of the earth and its several continents are in Mill's *International Geography*, Reclus' *Earth and Its Inhabitants*, Stanford's *Compendium of Geography and Travel*, and Suess' *Face of the Earth.*

TOPOGRAPHIC MAPS

See the map lists at the ends of the preceding chapters; for the continents see, among others, the Sydow and Habenicht, Kiepert, Oxford, Johnston, Wagner and Debes, Kuhnert, Gaebler, Goode, Rand McNally, and other physical maps, or the large originals of Howell's models, used as illustrations in this chapter.

For detailed maps of representative parts of each continent on the same scale see the International Map of the World on the scale of 1 : 1,000,000 (Pl. X), of which the following sheets are typical:

Boston, North K 19.
Paris, North M 31.
Lyon, North L 31.
Scotland—The Highlands, North O 30.
The Hebrides, North O 29.
Rome, North K 33.
Valencia, North J 30.
Constantinople, North K 35.
Budapest, North L 34.
Buenos Aires, South I 21.
Santiago de Chile, South I 18.
Iquique, South F 19.
Kenhardt, South Africa, South H 34.
Tokio, North I 54.

CHAPTER XVII

THE EARTH'S INTERIOR

Relation to Earth's Surface

Since Physiography treats of the earth's surface, it has to some seemed outside its province to deal with the interior condition. But the surface phenomena are so profoundly influenced by this interior condition, and in such important cases directly caused by it, that one is constantly encountering questions whose solution must be sought in the nature of the earth's interior. This has been illustrated again and again in the preceding pages, and in two or three places it has been deemed necessary to give some consideration to the interior condition in explanation of phenomena of the surface. Now that the surface features of the earth have been described with some fulness, it seems well to look to their causes in the light of the facts that have been presented.

Sufficient attention has already been paid to the causes of those land forms which result from the processes of denudation; but there are a series of phenomena whose causes have not been thoroughly considered. These are (1) the existence of the continent plateaus and ocean basins, (2) the changes in relative level of land and water, (3) mountain formation, (4) earthquakes, (5) vulcanism. These phenomena, though treated separately in the preceding chapters because of the difference in resulting land forms, are evidently closely related in cause. In the main they are surface expressions of conditions existing within the earth, even though the results at the surface are so widely different.

In this inquiry as to the underlying cause or causes for the phenomena in question, we are confronted by the most serious difficulties (1) because no direct observations of the interior have been possible, (2) because such indirect observations as have been possible, such as the surface phenomena which we seek to explain, are capable of explanation on more than one hypothesis, and (3) because, so far, critical facts have not been discovered which will eliminate the multiplicity of hypotheses. There is perhaps a fourth difficulty, namely, that more than one cause may actually be in operation to produce the same surface phenomenon. This is certainly the case with earthquakes, which, as we have seen, are caused in numerous ways.

In view of these difficulties it is not now possible to state either the exact condition of the earth's interior or the nature of the processes by which the phenomenon of vulcanism and diastrophism are brought about. The best that can be done is to put forward hypotheses; and in a book of this nature it will not be possible either to state all the hypotheses or to discuss them fully. All that can be attempted is to show approximately the state of our knowledge and to state some of the leading hypotheses.

Evidence of Heat within the Earth

Proof from Volcanoes and Igneous Rock. — There can be no question but that there is a great store of heat within the earth. Locally this is proved by the extrusion of molten rock from volcanoes. Over wider areas it is proved to have been the case in past ages by the existence of former ash deposits, lava flows, dikes, laccolites, and batholites, many of them in regions where there is no present day vulcanism.

Proof from Hot Springs and Deep Borings. — Hot springs, often in non-volcanic regions, give evidence of the presence of internal heat; and still more widespread are the deep wells, borings, tunnels, and mines, which, no matter in what part of the earth they are made, invariably show an increase in temperature with increasing depth.

Rate of Increase of Temperature with Depth. — This rate varies greatly, but is always sufficiently rapid to reach the melting point of rocks deep in the earth, if it continues. The rates of increase in temperature of 1° range from 20 to 250 feet, perhaps averaging 50 feet. An increase of 1° for every 60 or 70 feet amounts to a little less than 100° for each mile of depth, 1000° for ten miles, and at depths of 20 to 30 miles sufficient heat to melt rocks. The deepest boring, which is in the mines of South Africa, shows a temperature of 102° F. at 8000 feet.

Hypotheses as to Nature of Heated Interior. — It is not to be wondered that, with this knowledge, it was early inferred that the earth's interior was not only hot but liquid with a solid crust. This was the most simple and natural conclusion to draw from the facts. The hypothesis of internal liquidity has long been abandoned, but it is still believed by many that the interior is so highly heated that, where the pressure is relieved, it flows as a liquid. A slight modification of this hypothesis is that there are areas in which the pressure is sufficiently low to permit melting, and that there exists a liquid substratum, either general or local, between the crust and the heated solid interior. A rival hypothesis to that of a heated interior is that the heat is purely local, being generated in the earth itself.

Thus there are two diametrically opposed hypotheses, both necessarily admitting the existence of heat within the earth, but the one assuming it to be general and inherent in the earth from some primal state, the other assuming it to be localized and arising from conditions beneath the surface. These rival hypotheses will receive further consideration in later pages.

Condition of Earth's Interior

Evidence of Solidity. — As intimated in the preceding section, it is now quite generally agreed that the earth is essentially a solid, though admitting, of course, the presence of some liquid, as we must from the existence of volcanoes. By careful pendulum experiments it has been shown that the earth as a whole has a specific gravity of about 5.5, or five and a half times that of water. Since the specific gravity of the crust is between 2.4 and 3.3, it has been assumed that the interior consists of heavier elements than the crust, perhaps of iron and other metals. It is of course true, on the other hand, that the pressure of the interior will increase the density and consequently the specific gravity, though probably not to the extent required to account for the high specific gravity 5.5.

The evidence of solidity of the interior is along several different lines, as follows: (1) If liquid, with a rigid crust, this crust must have been growing thicker during the geological ages, and there should, therefore, be evidence of decreasing vulcanism from early ages to the present. This is not the case, and it is doubtful if at any earlier period there was greater vulcanism than in the period immediately preceding the present. (2) If the earth consisted of a crust with a liquid interior, the tidal forces would distort it twice each day, with resulting buckling of the rigid crust. (3) It has been shown that to produce the oceanic tides requires a solid sphere beneath the hydrosphere to a depth of not less than 2500 miles. (4) The astronomical phenomena of precession and nutation also demand an essentially solid globe, with the rigidity at least of glass. (5) The observed rate of travel of earthquake waves, after passing through the earth, detected by seismographs, is that of travel through a solid. (6) Finally, it has been urged that a solid crust could not develop on a liquid globe, for as soon as solidification took place, the greater specific gravity of the rock would cause it to settle into the liquid.

These evidences opposing liquidity of the earth's interior are now accepted universally as proof that the earth is a solid body.

Evidence of Plasticity. — Although solid, it does not follow that the rock of the earth's interior is incapable of flowage. It is a well-known fact that a rigid substance like ice is made to flow under pressure; and steel will also flow under sufficient pressure. In the same way, it is inferred, the rocks of the earth will flow as a viscous or plastic solid, when subjected to differential pressures of sufficient amount. This does not mean melting, nor necessarily the presence of high degree of heat, but merely the plastic flow of a solid, as in ice or steel.

The evidence of such flowage is of several kinds: (1) The rocks themselves, those formerly involved in intense mountain formation and now exposed by denudation, give evidence of having flowed without melting. (2) Gravity determinations point clearly to the flowage of rocks in the adjustment of differential loads and pressures, as is stated in the next section. (3) Adams has artificially imitated rock flowage in a series of careful experiments, thus demonstrating the rationality of the inference of rock flowage within the earth.

From these evidences there seems no basis for questioning the conclusion that the solid earth, whether hot or cold, is capable of deformation by the flowage of its rocky materials under high pressures, such as exist deep within the earth.

The solid interior of the earth appears to consist of a central core, occupying four-tenths of the radius, and an outer part of slightly different character. This has been deduced by Oldham from observations of the different rates of propagation of earthquake waves.

A different view of the earth's interior, however, is that it is partly gaseous. This has been proposed by Arrhenius, who holds that beneath the solid outer crust is a molten zone, and beneath that is a gaseous centre. Just as the molten portion is capable of becoming solid if the pressure were relieved, so the gaseous centre could become molten if there were lower temperature. The heat is believed to be above the critical temperatures (p. 443) of all the earth materials, but the enormous pressure is thought to give this gaseous centre a density and rigidity which is quite in accordance with all we know of the earth's interior as a whole. This gaseous theory in no way interferes with the idea of plasticity in the zone of rock flowage.

Evidence of Isostasy. — While the earth appears to be solid, it has long been known, from carefully conducted pendulum experiments, that there are notable differences in density in various parts. In general, the continents are regions of less density than normal for the earth, and the ocean basins are regions of greater density than normal. The reason for these differences is not known, but the fact is well established. Two very important deductions are drawn from the variations in density of earth material: (1) that water is drawn toward the areas of greater density, thus accounting in part for the distribution of oceanic waters over the globe, (2) areas of low density become regions of relative elevation, and areas of high density of depression. With variation in density in a given locality, or with variations in mass, adjustment will follow (1) by transfer of surface water, (2) by underflowage of the plastic rock.

The latter occurs as a result of an attempt to maintain isostatic adjustment. For example, Hayford finds the United States to be in a state of essential isostatic equilibrium, elevation being compensated for by decreased density. That is to say, a column from the crest of the Rocky Mountains downward, is no heavier than a column from the Mississippi valley downward, though some two miles higher. From his measurements he finds that the excess or defect does not exceed that equivalent to a stratum 250 feet thick at the density 2.67, the average density of the surface rocks.

The theory of isostasy, first outlined by Dutton, is that, if one start with a surface in isostatic equilibrium and take away from it, as by denudation, or add to it by deposition, the isostatic equilibrium is disturbed, and that there will at once follow an adjustment to bring about isostatic adjustment to the changed conditions. This change will be in the nature of flowage, or as Hayford calls it "an undertow," from surrounding regions of higher density to those of lesser density. This will cause a settling of the surface in the regions of high density, and a rise in those of low density until equilibrium is again established. This flowage will occur in what he calls the zone of compensation, which he places at not over 87 miles below the surface, nor less than 62 miles, with a probable mean depth of about 76 miles.

Besides causing change of level by direct flowage, Hayford infers secondary effects as a result of chemical change, and of temperature change. He also believes that this phenomenon of isostasy will account not merely for slow changes of level over broad areas, but also for the faulting and crumpling in mountain growth, due to the drag of the rigid crust by the "undertow."

That there is a tendency toward isostatic equilibrium in the earth's surface layers, and that movements of the crust occur as a result of disturbance of this equilibrium is now quite generally admitted; and it seems that Hayford's careful geodetic studies demonstrate it. There are, however, very grave difficulties in the way of acceptance of isostasy as an explanation for the larger earth features, and for the greater earth movements. For instance, ocean basins, the greatest depressions of the earth, are not the seat of the heaviest deposits, as would be expected on the theory of isostasy. This theory also fails to account for the periods of excessive vulcanism or diastrophism; for the long intervals of freedom from these with accompanying base-levelling; for the rise of mountains in areas of heavy deposition where normally depression should continue; and for other significant phenomena.

It seems, therefore, that while we may accept isostasy as a potent agent of change on the earth's surface, it fails to account for all diastrophic movements. It is one reason for the observed changes, but not the sole reason; nor does it seem probable that it is the most potent.

Changes in Ocean Level. — There is general agreement that the level of the oceanic waters is subjected to changes of considerable amount in the course of long periods of time. The problem is a complex one and does not admit of definite mathematical statement because of the varied factors involved and because of the lack of data for exact calculation; but of the broad conclusion that the ocean level fluctuates, there can be no doubt.

Some of the causes for such fluctuation are as follows: (*A*) *Causes for Rise in Sea Level:* (1) The wearing down of the lands and the deposit of sediment in the ocean raises the level, and this cause may give rise to a very perceptible change during periods of long-continued denudation. (2) The lowering of land beneath the sea will displace ocean water and cause a rise of the level. (3) The addition of water to the oceans from volcanic and other deep-seated sources increases the volume of ocean water, and, therefore, has a tendency to raise its level. (4) An elevation of sea floor, or the building of volcanic cones there, displaces ocean water and causes a rise in sea level. (5) The melting and disappearance of glaciers adds water to the ocean level and causes it to rise.

(*B*) *Causes for Depression of Sea Level:* (1) The withdrawal of ocean water in the processes of weathering is a cause for depression of sea level. (2) Waters locked up in glaciers is important in the same way. (3) Depression of sea level will follow a sinking of parts of the ocean bottom.

(*C*) *Causes for Both Rise and Fall of Sea Level:* (1) Variation in rate of rotation or in position of the axis of rotation would necessarily be followed by a redistribution of the water, causing a rise in one place and a depression in another. (2) Changes in the centre of gravity will also result in redistribution of water, drawing it toward one part and away from the other. (3) The lateral attraction of land masses or ice masses will draw water toward them and away from other places.

These several causes may operate at the same time, perhaps counterbalancing one another, or, if working together, producing a combined result, the product of the two.

In these ways it is possible to account for some of the apparent changes of level of the land; but, as we have seen, not for all, since there is undoubted proof that the crust of the earth itself is in motion. The phenomena of the ocean margin, therefore, as well as of the land itself, demand some movements of the lithosphere and call for an interpretation of the condition of the earth's interior. Indeed, among the causes given for changes in ocean level are diastrophic movements in the ocean bed; and also it is to be noted that the extrusion of lava and of volcanic water from within the earth must be accompanied by compensating downward movements of the crust.

In the present state of our knowledge it is impossible to assign to the several causes outlined above either numerical value or relative importance. Nor is it possible to state whether, in the total, the changes of level of ocean waters are more or less important than changes in level of the lands. It is, however, generally agreed that both causes are operative in modifying the earth's surface. At present the ocean waters rise higher, or the continents sink lower, than in a recent period, as indicated by the great extent of the continental shelf, and by the many drowned coast lines in both hemispheres. In earlier geological times the ocean waters rose even higher than now on the continents, though whether this was a general condition or merely local cannot be positively determined.

Summary of Conclusions. — In the preceding pages the attempt has been made to keep, in the main, to a statement of points upon which there is a fairly uniform agreement and which seem to be pretty well established. In summary, these points are as follows: (1) The earth's interior is solid; (2) it is, however, in a state of sufficient plasticity to admit of flowage and isostatic adjustment; (3). there are changes in the level of the ocean as well as of the crust; (4) there is heat within the earth.

When we arrive at the latter point, we come to a great divergence of views and must enter upon a consideration of hypotheses upon which there is no general agreement. These hypotheses are of two main types: (1) those based upon a belief in general interior heat, (2) those assuming local areas of heat. We will next consider these hypotheses, beginning with that of general heat.

Possible Sources of General Interior Heat

Relation to Various Ideas of Earth Origin. — There are at present several hypotheses to account for the origin of the earth, each having its adherents, and each varying in relation to the source of general heat in the interior of the earth. The first and oldest of these is the *Nebular Hypothesis;* among the other and more recent ones are the *Meteoritic Hypothesis* and the *Planetesimal Hypothesis.*

The Nebular Hypothesis. — According to this hypothesis, which is largely the work of Laplace, the solar system was originally a highly heated gaseous mass or *nebula* slowly rotating, and occupying all the space of the solar system and extending even beyond it, that is, with a diameter in excess of 6,000,000,000 miles. As this gaseous mass lost heat by radiation, it contracted; and, one by one, rings developed, in which, around some centre of greater density, the gaseous particles gathered, forming gaseous spheres which rotated around an axis, and revolved in the direction of the original rotation of the parent nebula. One by one the planetary spheres of the solar system developed, and the satellites developed in similar way from the individual planetary spheres.

As cooling continued, the gases condensed to liquid and then, in most of the spheres, to solid state, growing smaller as they became cooler. The sun, the central part of the ancient nebula, and the largest body of the solar system, is still glowing hot. So small a body as the moon has cooled down to completely solid state, and both its ocean and its atmosphere have disappeared within its cold mass. Jupiter, the largest planet, is still so hot that its atmosphere includes the waters as well as the elements of the air. The earth is in a state intermediate between the moon and Jupiter, with a heated interior, a solid crust, and an atmosphere and hydrosphere resting upon the lithosphere.

This is not the place for a discussion of the nebular hypothesis. It held sway for a long time and long seemed a rational explanation of the origin of the earth, having well-nigh universal acceptance. It is still held by many to be the most rational hypothesis yet put forward for the origin of the earth. Latterly, however, it has been subjected to criticism, and serious objections have been urged against it, while at the same time rival hypotheses have been put forward.

The general interior heat is thought, under this hypothesis and the modification which supposed the earth to still retain a gaseous centre (p. 614), to be derived from the cooling of the gaseous nebula.

The Meteoritic Hypothesis. — One of the recent rival hypotheses is the *Meteoritic Hypothesis*, which conceives the origin to have been the collision of particles of cosmical bodies swarming in space. These particles, which may be called meteors, collide with such force as to become vaporized by the heat; and, as a mass grows by successive increments, it exerts a sufficient gravitative attraction to draw still more meteoritic matter to it. Thus the mass grows larger, and becomes heated by collision. The members of the solar system are of this origin, and the heat of the earth's interior is thought to be still retained from this former state.

The Planetesimal or Spiral Nebula Hypothesis. — This hypothesis assumes that the earth has been a cold mass and gradually became somewhat warmer. Instead of being a planet made by the collision of meteorites, as in the preceding hypothesis, it is thought to have been formed by the gathering-in of masses of nebulous matter or planetesimals, to a centre corresponding to one of the so-called "knots" on the spiral nebulæ. The heat is thought to have been formed by internal compression and to have developed from the earth's centre outward, as the earth grew by the accretion of layer after layer of planetesimals. Moreover, during the earth's slow growth, this hypothesis assumes that heat was carried by volcanic action from great depths to points near and at the earth's surface, a process thought to be still in operation at a diminished rate.

The Contractional Hypothesis

The Shrinking Interior of the Earth. — Assuming the earth's interior to be heated and surrounded by a solid cold crust, it follows that, as the heat is slowly conducted to the surface and radiated into space, the earth is slowly growing smaller. As the interior shrinks, the rigid outer crust settles upon it; but, being itself already cooled, it does not sink equally. Consequently, to fit the shrinking interior it must become wrinkled. The comparison is often made to an apple, whose interior shrinks by loss of water, causing the more rigid skin to settle irregularly and wrinkle. Another comparison may be made to a ball around which is placed a leather or cloth cover larger than the ball. On pressing this down to fit the surface of the ball, it is necessarily wrinkled.

This contractional hypothesis has long been before the scientific world, and it has many adherents. By many it is thought to be the main underlying cause for the phenomena of vulcanism and diastrophism; though isostasy is generally admitted as a supplementary cause for diastrophic phenomena.

Subsidence and Lateral Thrust. — On the basis of the contractional hypothesis it is inferred that the surface of the earth is slowly subsiding; but, in certain areas, subsidence is in progress in excess, as in the ocean bottoms. From these areas of subsidence lateral thrusts are applied, actually pushing up the crust in plateau-like areas, as would occur in fitting the cover to a ball which is too small for it. This lateral thrust may even cause local wrinkling, such as is found along mountain chains. Moreover, by the downward thrust of the sinking areas, the heated rock may be made to flow away from the areas of depression toward and under the areas of uprising. This would account for the great batholitic masses beneath mountains; and, rising along the fissures opened in the rigid crust by the movements to which it is subjected, this heated rock may be squeezed out in fissure eruptions, or forced out of volcanic vents, partly by the pressure, partly by the expansive force of included gases.

The contractional hypothesis is thus made to account for the major phenomena of vulcanism and diastrophism, though admitting of the operation of isostasy, and also of upward movements due to intrusion of lava and downward movements resulting from the extrusion of lava from beneath areas of the crust. By this hypothesis the ring of lofty mountains, numerous volcanoes, and frequent earthquakes are explained as a result of lateral thrust from the subsidence in the great Pacific basin. The continental slope surrounding the continents is interpreted as the approximate boundary between areas of depression and areas of either (1) freedom from depression, or (2) of less depression than in the ocean basins. The continental slope is on this theory either (1) the upthrow side of fault lines, or (2) the site of a sharp fold, or (3) sometimes one, sometimes the other.

Objections to Contractional Hypothesis. — Although the contractional hypothesis seems so natural a sequel to those hypotheses of earth origin which assume a heated condition, and although it so satisfactorily accounts for such a number of phenomena of diastrophism and vulcanism, it cannot be considered established, nor is it universally considered satisfactory. There are a number of serious difficulties in the way of accepting it as an adequate hypothesis, among these being the following: (1) Even granting that the forces developed by contraction are concentrated along very narrow belts, the results produced in the recent elevation of mountain chains seems far too great for the cause proposed. (2) While upon the contractional hypothesis a reason is assigned for the growth of mountains around the Pacific, there is no equally adequate reason for the recent rising of mountains along other belts, as, for example, the east-west mountain girdle. Though associated with areas of depression, these are not on the border of great areas of subsidence from which extensive lateral thrust is to be expected. (3) Even around the Pacific the mountain chains have a form indicating an origin from the land side rather than from the ocean. The great mountain loops, so typically shown in Asia, but also developed elsewhere, give the appearance of crustal movements *toward* the ocean, not away from it. It is difficult to explain these loops by any theory of thrust from the ocean. (4) The theory gives no explanation of (*a*) the development of mountains along one belt, and subsequent abandonment of that belt; (*b*) of the diminution of volcanic activity such as has been in progress in the recent past; (*c*) of the long periods of freedom from diastrophism and the development of peneplains. The earth history appears to have been one of intermittent activity, with periods of mountain growth and vulcanism, between which were periods of sufficient inactivity to permit of the widespread reduction of land surfaces. The present appears to represent a waning stage in a period of earth activity, preceded by very great activity, in which peneplains were uplifted, new mountains were formed, and old mountains revived, while great volcanic activity developed. Prior to this stage was a period of sufficient activity to permit of widespread peneplanation in Europe and America, and in at least portions of Asia and South America.

Possible Sources of Local Earth Heat

The Three Suggested Sources. — Hypotheses have been put forward to explain the phenomena of diastrophism and vulcanism on the assumption of local development of heat within the earth. Some of these have been intended solely to account for such localization of vulcanism as has been observed; others are advanced in explanation of volcanic and diastrophic phenomena in general. There are three known causes of phenomena which, whether the earth is assumed to be cold or hot in the interior, are capable of generating heat within the earth: (1) chemical change, (2) radioactivity, (3) mechanical movements.

Chemical Change. — It has been pointed out that, if the earth consists of unoxidized metallic elements, with an oxidized crust, the percolation of water down to the unoxidized portion would give rise to processes of oxidation which would generate heat. Granting the postulates, the result is certain; but it is not so certain that sufficient heat would be generated to give rise to the phenomena of vulcanism. Furthermore, there is a limit to the downward percolation of water, which is confined to the zone of fracture. It might be assumed that there are other chemical changes of unknown nature in the subcrustal portions of the earth; but this rests upon scant basis.

Radioactivity. — Recently radioactivity has naturally been invoked as a source of visible earth heat, and as an explanation of both diastrophic and volcanic phenomena. So little is known about this property, and so much less about the radium content of the earth, that this theory, which is necessarily of very recent origin, cannot have been very thoroughly considered or tested.

Crustal Movements. — Movements in the earth's crust, or in the sub-crustal portions of the earth, are certainly capable of generating heat, and changes of pressure are also competent to produce heat. Thus it has been pointed out that in connection with isostatic adjustment, temperature changes of importance necessarily follow. And surely, in such movements as give rise to mountain folding, great development of heat results. The theory has been put forward that sufficient heat may be developed in such places to cause extensive melting of the rocks and perhaps to be one cause, if not the main one, for volcanic activity in areas of mountain growth.

Objections to Hypotheses of Local Heat. — While it must certainly be admitted that heat is produced by each of these causes, no one of them, on the basis of any of the processes mentioned above, is capable of satisfactorily accounting for the phenomena of diastrophism and vulcanism observed on the earth. Even granting the maximum efficiency, they still fail in some of the same important respects as the contractional hypothesis does: they do not explain (1) the peculiar mountain loops, (2) the localization of movements along belts, (3) the recent diminution of volcanic activity, (4) the intermittent activity with periods of relative inactivity.

Hypothesis of Change of Earth's Axis of Rotation

The Problem of Cause for such Change. — It has been suggested, always with extreme caution, that there may have been change in the axis of the earth. There is no known cause for a change in the earth's axis of rotation, and scientific men have naturally looked askance at this hypothesis, because it makes appeal to an unknown cause. It is, therefore, with grave doubt, and with due caution, that it is brought forward here. If a cause for such a change were found, an hypothesis for the diastrophic and volcanic phenomena of the earth could be formulated which would have a high degree of merit; by it, also, other puzzling phenomena would find explanation. There may be hope that such a cause will be found, now that it is known there is actually a variation of the earth's axis, though of small amount.

In the absence of a known cause for change in the earth's axis, or even of a rational hypothesis for such a change, a tentative suggestion of its possibility is as far as one is warranted in going. It is interesting to note, however, how many phenomena could be accounted for by a change in the axis of the earth's rotation, and how readily it would solve some of the most puzzling phenomena of the earth's surface of the present and past times.

Relation of Shifted Axis to Glaciation. — If we could assume a change in the axis of the earth's rotation, we would have an immediate and effective answer to the problem of the cause of continental glaciation in Europe and America during the Glacial Period. It would also account for the puzzling fact that the ice sheets were centred around the North Atlantic basin, and were absent from other far northern regions such as northern Alaska and Asia. Here would be explanation of the apparent diminution of glaciation toward the north. One of the most puzzling facts concerning former glaciation is the presence of great ice sheets in former geological periods in various parts of the world, and notably in South Africa, where an ice sheet developed in the tropical zone and moved toward the polar region. A change in the axis of the earth's rotation would satisfactorily explain this glaciation, the most difficult of all to account for by current theories of climatic change.

Relation to Earth Movements. — Should the position of the earth's axis of rotation be changed, whether slowly or abruptly, there would follow, first an immediate change in distribution of water on the surface, with accompanying rise of the sea level in parts of the earth and lowering in others. More slowly, and lagging behind, would follow an adjustment of the lithosphere to the new axis of rotation and the development of the oblate spheroid form in accordance with the position of the new axis. During this adjustment there would be flow in the zone of flowage, and a dragging of the rigid outer crust, with accompanying changes of level, and local, linear areas of crumpling and faulting. Heat would necessarily result from these movements, and, quite conceivably, heat enough to cause extensive melting of rocks along the areas of greatest disturbance.

Relation to Volcanic and Diastrophic Activity. — If such changes could be assumed, a number of the most puzzling phenomena of diastrophism and vulcanism would find explanation. For example, during the periods when no changes in the earth's axis occurred, there would be rest from volcanic and diastrophic activity, denudation would have full sway, the continents would be slowly worn down, and extensive peneplanation would result. Such seems to have been the case in the early stages of the Tertiary Period, and it is noteworthy that warm temperate flora and fauna lived far within the Arctic, giving rise to extensive coral beds, for example, in Spitzbergen, in latitude 79°, where now is a land of snow and ice.

If then the period of quiet is interrupted by a change in the axis, a warm temperate region may be transformed to a frigid region of continental glaciers, changes both of land and sea level will follow, and mountain folding may occur along favourable lines, as the crust is dragged forward on the undertow developed in the zone of flowage. Lofty mountains may rise, lava floods may issue from fissures in the crust, and volcanic mountains may be built up by the extrusion of lava, formed by the heat due to the crustal and sub-crustal movements. Both mountain formation and volcanic activity would slowly die out as adjustment was reached.

Relation to Folding and Faulting. — The forward drag of the rigid crust would account for the great mountain loops, such as those of

Asia, which seem to have moved outward from some point to the north. It would explain the great thrust faults, by which blocks of the crust have been dragged forward many miles and also the extensive compression of originally horizontal strata, so that they now occupy a much smaller horizontal space than formerly. In eastern United States it is estimated that there has been an apparent shortening of the arc of the earth's surface by fully 50 miles, and in other mountain regions similar apparent shortening has occurred.

Relation to Volcanic Recurrence. — On the theory of a globe originally heated and subjected to continued loss of heat during the millions of years of geological time, it is exceedingly difficult to explain the apparent fact that volcanic activity has not been diminishing progressively. It is also difficult to explain the apparently shallow source of the lava of volcanoes, though this may be due to the rise of batholitic masses into the crust. On the theory of change in the axis, both of these phenomena are readily explained, for the heat necessary for vulcanism is developed only at intervals.

Summary of Results of Shifting Earth's Axis. — Could some adequate cause be found for a change in the position of the axis of earth's rotation, some of the obscure problems of earth form and condition would be more easily and satisfactorily explicable than under any theory at present before us. Present and recent diastrophism and vulcanism would be explained; the location of areas of disturbance along different lines in different ages would be understandable; changes of climate, including periods of glaciation, would not prove such puzzling phenomena; and the limitations placed upon the length of geological time by physicists, who base their estimates upon the rate of cooling of a formerly heated globe, would lose their apparent force. Unfortunately, however, until some adequate cause for such changes appears, the hypothesis of change in the earth's axis can be put forward only in a tentative way.

Age of the Earth

Geological Time is of Great Duration. — Throughout the preceding chapters the phenomena of the earth's surface have been interpreted on the basis of the assumption that geological time has been of great duration. Indeed, it has become evident, from a study of the evolution of the forms of the land, that these can be explained only on such an assumption. To deposit thousands of feet of sedimentary strata, to raise these into mountain folds, and to reduce the folded mountains to the condition of a peneplain, each requires long time periods; and, since these processes have been repeated again and again, it is evident that there must have been a vast lapse of time during the geological past. From such evidences, as well as from others furnished by a study of geological history, the conclusion has become generally accepted that the period of geological time can be estimated only in millions of years.

Naturally there has been a desire to reckon geological time more definitely than this, and many efforts have been made to that end. From such efforts there has been wide divergence of results, though all agree in the one conclusion that the age of the earth is very great.

Estimates by Physicists. — The estimates that, seemingly, have the best basis, and that handle the problem with most mathematical exactness, are those of physicists who have followed three main lines of argument: (1) the rate of cooling of the earth to its present state, (2) the age of the sun's heat, (3) the effect of tidal retardation upon the rate of earth's rotation. From the first line of argument the conclusion has been reached that the earth cannot have required more than 20,000,000 years to have cooled down to its present state, assuming a heated interior with cold crust. From the second it has been concluded that the sun cannot have supplied heat to the earth at the present rate for a period of more than 20,000,000 years. On the basis of the influence of tidal retardation, a similar age has been deduced, and it has been agreed by physicists that the physical evidence "reduces the possible period which can be allowed to geologists to something less than 10 millions of years."

There is a seeming mathematical exactness in these calculations which has perhaps led to placing rather more reliance upon them than is really warranted. In each case there are fundamental basal assumptions which, if incorrect, destroy the value of the whole analysis. It is assumed, for instance, that the earth's interior is highly heated; it is assumed that there is no renewal of supply to the sun's heat; and it is assumed that a greater oblateness of the earth due to an earlier, more rapid rotation, would still be recognizable. No one of these assumptions is established, and there are reasons for doubting the correctness of some of them.

Estimates by Geologists. — There seems really little reason for placing more reliance upon these figures obtained by physical analysis than upon the much more vague estimates of geologists. Considering the great extent of sedimentation in past ages, the vast results of denudation, and the marvellous evolution of animal and plant life, revealed by the geological record, and assuming a past rate for these processes not greatly unlike that of the present, geologists have become profoundly impressed with the vast lapse of time demanded for them. Some have made rough estimates, admittedly inexact, and most of them have been far in excess of the physical estimates. A conservative geological estimate would be at least 60 to 100 million years; and, to some, many times this period seems demanded to account for the phenomena of earth history revealed by geological study.

The physiographer, though interpreting the forms of the earth as they at present exist, must of necessity deal to some extent with this question of the lapse of past time, since the development of present land forms is an outcome of a long series of past changes. The study and solution of the problem is, however, within the province of the geologist and physicist rather than the physiographer. To him the point of prime importance is that there has been a vast lapse of time, during which the complex processes of denudation, diastrophism, and vulcanism have been in operation. Whether this time period is 20,000,000 years or one hundred times that amount, must be left to the physicist and geologist to settle, but such evidence as the physiographer gathers points toward the larger rather than the smaller estimate.

References to Literature

F. D. Adams. Experimental Investigation into the Flow of Rocks, Amer. Journ. Sci., Vol. 179, 1910, pp. 465–487; Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust, Journ. Geol., Vol. 20, 1912, pp. 97–118.

F. D. Adams and J. T. Nicolson. Experimental Investigation into the Flow of Marble, Phil. Trans. Roy. Soc., London, Vol. 195, 1901, pp. 363–401.

S. Arrhenius. Worlds in the Making, New York, 1908, 230 pp.; Die Feste Erdkruste und das Erdinnere, Lehrbuch der Kosmischen Physik, Leipzig, 1903, pp. 278–347.

R. S. Ball. The Earth's Beginning, London, 1901, 384 pp.

J. Barrell. The Strength of the Earth's Crust, Journ. Geol., Vol. 22, 1914, pp. 28–48, 145–165, 209–236, 289–314.

E. de Beaumont. Notice sur les Systèmes des Montagnes, Paris, 1852, 1143 pp.

H. T. de la Beche. A Geological Manual, Philadelphia, 1832, 535 pp.

G. F. Becker. Relations of Radioactivity to Cosmogony and Geology, Bull. Geol. Soc. Amer., Vol. 19, 1908, pp. 113–146; The Age of the Earth, Smithsonian Misc. Collections, No. 1936, Washington, 1910, 28 pp.

M. Bertrand. Déformation Tetraédrique de la Terre et Déplacement du Pole, Comptes Rendus Acad. Sci. Paris, Vol. 130, 1900, pp. 449–464.

W. Bowie. Effect of Topography and Isostatic Compensation upon the Intensity of Gravity, Special Publication 12, U. S. Coast and Geodetic Survey, Washington, 1912; Amer. Journ. Sci., 4th series, Vol. 33, 1912, pp. 237–240; Isostasy and the Shape and Size of the Earth, Science, N. S., Vol. 39, 1914, pp. 697–707.

T. C. Chamberlin. An Attempt to Test the Nebular Hypothesis by the Relation of Masses and Momenta, Journ. Geol., Vol. 8, 1900, pp. 58–73; On a Possible Function of Disruptive Approach in the Formation of Meteorites, Comets and Nebulæ, *ibid.*, Vol. 9, 1901, pp. 369–392; The Bearing of Radioactivity on Geology, *ibid.*, Vol. 19, 1911, pp. 673–695; *ibid.*, Trans. Illinois Acad. Sci., Vol. 23, 1912, pp. 57–75; Fundamental Problems of Geology, Year Book 3, Carnegie Institution, Washington, 1904, pp. 195–258; Diastrophism and the Formative Processes, Journ. Geol., Vol. 21, 1913, pp. 517–533, 577–587, 673–682; *ibid.*, Vol. 22, 1914, pp. 131–144, 268–274, 315–345.

T. C. Chamberlin, F. R. Moulton, and Others. The Tidal and Other Problems, Publication 107, Carnegie Institution, 1909, 264 pp.

T. C. Chamberlin and R. D. Salisbury. Geology, Vol. 2, 1906, pp. 3–81; *ibid.*, Vol. 1, 1905, pp. 559–569.

James Croll. Climate and Time, New York, 1875, 577 pp.; Climate and Cosmology, Edinburgh, 1885, 327 pp.; Nature, Vol. 18, 1878, pp. 267–268.

W. O. Crosby. Origin and Relations of Continents and Ocean Basins, Proc. Bost. Soc. Nat. Hist., Vol. 22, 1884, pp. 443–485.

J. D. Dana. Origin of Igneous Rocks of the Earth, Origin of Continents, Amer.

Journ. Sci., 2d series, Vol. 2, 1846, pp. 335–353; Earth Shaping, Mountain Making, and the Attendant Phenomena, Manual of Geology, 4th edition, 1896, pp. 345–396; Length of Geological Time, *ibid.*, pp. 1023–1026.

N. H. Darton. Geothermal Data from Deep Artesian Wells in the Dakotas, Amer. Journ. Sci., Vol. 155, 1898, pp. 161–168.

G. H. Darwin. Scientific Papers, Vol. 2, Tidal Friction and Cosmogony, Cambridge, 1908, 516 pp.; The Tides and Kindred Phenomena in the Solar System, Boston, 1898, London, 1911, 437 pp.

W. M. Davis. The Bearing of Physiography upon Suess' Theories, Amer. Journ. Sci., Vol. 169, 1905, pp. 265–273.

C. E. Dutton. A Criticism upon the Contractional Hypothesis, Amer. Journ. Sci., 3d series, Vol. 8, 1874, pp. 113–125; On Some of the Greater Problems of Physical Geology (including isostasy), Bull. Phil. Soc. Washington, Vol. 11, 1889, pp. 51–64.

B. K. Emerson. The Tetrahedral Earth and Zone of the Intercontinental Seas, Bull. Geol. Soc. Amer., Vol. 11, 1900, pp. 61–106.

O. Fisher. Physics of the Earth's Crust, London, 1881, 299 pp.

A. Geikie. Text-Book of Geology, 4th edition, London, 1903, pp. 13–83, 351–397.

G. K. Gilbert. The Strength of the Earth's Crust, Bull. Geol. Soc. Amer., Vol. 1, 1889, pp. 23–27; Continental Problems, *ibid.*, Vol. 4, 1893, pp. 179–190; New Light on Isostasy, Journ. Geol., Vol. 3, 1895, pp. 331–334; Earth, Universal (Johnson's) Encyclopedia, Vol. 2, 1893, pp. 886–892; The Moon's Face, Bull. Phil. Soc. Washington, Vol. 12, 1893, pp. 241–292; Rhythms and Geologic Time, Science, N. S., Vol. 11, 1900, pp. 1001–1012; Interpretation of Anomalies of Gravity, Prof. Paper 85-C, U. S. Geol. Survey, 1913, pp. 29–37.

W. L. Green. Vestiges of a Molten Globe, London, 1875, and Honolulu, 1887.

J. W. Gregory. The Plan of the Earth and Its Causes, Geog. Journ., Vol. 13, 1899, pp. 225–251; Mill's International Geography, New York, 1907, pp. 36–45; The Making of the Earth, New York, 1912, 256 pp.

É. Haug. Les Theories Orogenique, Traité de Géologie, Paris, 1907, pp. 511–536.

J. F. Hayford. The Figure of the Earth and Isostasy from Measurements in the United States, U. S. Coast and Geodetic Survey, Washington, 1909; Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy, *ibid.*, 1910; The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity, International Geodetic Association, 16th Report, Vol. 1, pp. 365–389; *ibid.* (with W. Bowie), Special Publication 10, U. S. Coast and Geodetic Survey, 1912; Relations of Isostasy to Geodesy, Geophysics, and Geology, Science, Vol. 33, 1911, pp. 199–208; Isostasy, a Rejoinder to the Article by Harmon Lewis, Journ. Geol., Vol. 20, 1912, pp. 562–578.

W. H. Hobbs. Mechanics of Formation of Arcuate Mountains, Journ. Geol., Vol. 22, 1914, pp. 71–90, 166–188, 193–208.

A. Holmes. The Age of the Earth, London, 1913, 196 pp.

J. Joly. Uranium and Geology, Nature, Vol. 78, 1908, pp. 456–466; Radioactivity and Geology, 1909, p. 211; An Estimate of the Geological Age of the Earth, Trans. Roy. Soc. Dublin, series 2, Vol. 7, 1899, pp. 23–65; Rept. Brit. Assoc. Adv. Sci., 1900, pp. 369–379.

Immanuel Kant. Allgemeine Naturgeschichte und Theorie des Himmels, Königsberg, 1755.

Clarence King. The Age of the Earth, Amer. Journ. Sci., 3d series, Vol. 45, 1893, pp. 1–20; Ann. Rept. Smithsonian Institution, 1892–1893, pp. 335–352.

P. S. Laplace. Système du Monde, Paris, 1796; edition in English, 2 vols., Dublin, 1830,— Considerations on the System of the World, Vol. 2, pp. 324–342.

A. de Lapparent. De la Mesure du Temps Parles Phénomènes de Sédimentation, Bull. Geol. Soc. France, Vol. 18, 1890, pp. 351–355; La Destinée de la Terre Férme et Durée des Temps Geologique, Brussels, 1891, 38 pp.; Sur la Symétrie Tetraédrique du Globe Terrestre, Comptes Rendus Acad. Sci. Paris, Vol. 130, 1900, pp. 614–619.

J. Le Conte. Earth-Crust Movements and their Cause, Bull. Geol. Soc. Amer., Vol. 8, 1897, pp. 113–126; Igneous Agencies, Elements of Geology, New York, 1885, pp. 76–132; General Form and Structure of the Earth, *ibid.*, pp. 164–170.

H. Lewis. The Theory of Isostasy, Journ. Geol., Vol. 19, 1911, pp. 603–626.

J. N. Lockyer. The Meteoritic Hypothesis, London, 1890, 560 pp.; Chemistry of the Sun, New York, 1887.

A. E. H. Love. The Gravitational Stability of the Earth, Phil. Trans. Roy. Soc., Vol. 207, 1908, pp. 171–241; Dynamical Theory of the Shape of the Earth, Nature, Vol. 76, 1907, pp. 327–332.

Sir Charles Lyell. Comparative Duration of the Glacial and the Antecedent Tertiary, Secondary, and Primary Epochs, Principles of Geology, 11th edition, 1873, Vol. 1, pp. 300–304; Causes of Earthquakes and Volcanoes, *ibid.*, Vol. 2, pp. 198–213.

W J McGee. The Gulf of Mexico as a Measure of Isostasy, Amer. Journ. Sci., Vol. 44, 1892, pp. 177–192.

A. A. Michelson. Preliminary Results of Measurements of the Rigidity of the Earth, Journ. Geol., Vol. 22, 1914, pp. 97–130. See also **H. G. Gale**, Science, N. S., Vol. 39, 1914, pp. 927–933.

F. R. Moulton. The Shape of the Earth, Journ. Geog., Vol. 2, 1903, pp. 481–486, 521–527; The Motions of the Earth, *ibid.*, Vol. 3, 1904, pp. 145–150, 213–222; An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics, Astrophysical Journ., Vol. 11, 1900, pp. 103–130; The Spiral Nebula Hypothesis, Introduction to Astronomy, New York, 1913, pp. 463–487.

P. G. Nutting. Isostasy, Oceanic Precipitation, and the Formation of Mountain Systems, Science, N. S., Vol. 34, 1911, pp. 453–454.

R. D. Oldham. Constitution of the Interior of the Earth, Quart. Journ. Geol. Soc., Vol. 62, 1906, pp. 456–473.

F. L. Ransome. The Great Valley of California, Bull. Dept. Geol. Univ., California, Vol. 1, 1896, pp. 371–428.

T. M. Reade. Measure of Geological Time, Geol. Mag., Vol. 10, 1893, pp. 99–100; Chemical Denudation in Relation to Geological Time, London, 1879.

W. B. Scott. The Internal Constitution of the Earth, Introduction to Geology, 2d edition, New York, 1907, pp. 90–96; The Causes of Folding and Dislocation, *ibid.*, pp. 358–368.

E. H. L. Schwartz. Causal Geology, London, 1910, 248 pp.

T. J. J. See. The Cause of Earthquakes, Mountain Formation, and Kindred Phenomena, Proc. Amer. Phil. Soc., Vol. 45, 1906, pp. 274–414; On the Temperature, Secular Cooling, and Contraction of the Earth, *ibid.*, Vol. 46, 1907, pp. 191–299; The New Theory of Earthquakes and Mountain Formation, *ibid.*, pp. 369–415.

N. S. Shaler. A Comparison of the Features of the Earth and the Moon, Smithsonian Contributions, Vol. 34, 1903, 79 pp.

W. J. Sollas. The Age of the Earth and Other Geological Studies, London, 1905, 328 pp.

J. W. Spencer. Relation between Terrestrial Gravity and Observed Earth Movements of Eastern America, Amer. Journ. Sci., 4th series, Vol. 35, 1913, pp. 561–573.

R. J. Strutt. Radio-Active Changes in the Earth, Nature, Vol. 79, 1908, pp. 206–208.

E. Suess. Das Antlitz der Erde, 4 vols., in German, French, and English.

F. B. Taylor. Bearing of the Tertiary Mountain Belt on the Origin of the Earth's Plan, Bull. Geol. Soc. Amer., Vol. 21, 1910, pp. 179–226.

W. Thomson (Lord Kelvin). On the Secular Cooling of the Earth, Trans. Roy. Soc. Edinburgh, Vol. 23, 1862; On the Age of the Sun's Heat, Macmillan's Magazine, 1862, — see Thomson and Tait's Treatise on Natural Philosophy, London, 1883, Cambridge, 1890, Part 2, pp. 468–494; The Internal Condition of the Earth as to Temperature, Fluidity, and Rigidity, Popular Lectures and Addresses, Vol. 2, pp. 299–318; The Age of the Earth as an Abode Fitted for Life, Science, N. S., Vol. 9, 1899, pp. 665–674, 704–711.

S. D. Townley. The Shifting of the Earth's Axis, Pop. Sci. Monthly, Vol. 75, 1909, pp. 417–434.

Warren Upham. Estimates of Geologic Time, Amer. Journ. Sci., 3d series, Vol. 45, 1893, pp. 209–220.

C. R. Van Hise. Estimates and Causes of Crustal Shortening, Journ. Geol., Vol. 6, 1898, pp. 10–64; Deformation of Rocks, *ibid.*, Vol. 4, 1896, pp. 195–213, 312–353, 449–483, 593–629; Vol. 5, 1897, pp. 178–193; Metamorphism of Rocks and Rock Flowage, Amer. Journ. Sci., Vol. 156, 1898, pp. 75–91; A Treatise on Metamorphism, Monograph 47, U. S. Geol. Survey, 1904, 1286 pp.

C. D. Walcott. Geologic Time as Indicated by the Sedimentary Rocks of North America, Journ. Geol., Vol. 1, 1893, pp. 639–676.

T. L. Watson. Underground Temperatures, Science, N. S., Vol. 33, 1911, pp. 828–831; *ibid.*, Vol. 34, 1911, pp. 125–126.

B. Willis. A Theory of Continental Structure Applied to North America, Bull. Geol. Soc. Amer., Vol. 18, 1907, pp. 389–412; What is Terra Firma? — A Review of Current Research in Isostasy, Ann. Rept. Smithsonian Institution, Washington, 1911, pp. 391–406.

Alexander Winchell. Comparative Geology, Chicago, 1883, 642 pp.

R. S. Woodward. The Mathematical Theories of the Earth, Smithsonian Rept. for 1890, pp. 183–200; The Century's Progress in Applied Mathematics, Bull. Amer. Math. Soc., Vol. 6, 1900, pp. 147–148.

CHAPTER XVIII

TERRESTRIAL MAGNETISM

Magnetism of the Earth

The Compass. — A familiar instrument is the compass, whose needle we think of as always pointing north. Any magnetized bar or needle of magnetized steel so suspended that it will swing freely in a horizontal plane is a compass; in different parts of the world it points in quite different directions. At some places in the world the compass needle does set itself exactly north and south; that is, in the direction of the true or geographical poles. When Admiral Markham was travelling due north toward the North Pole in 1876, he was steering east-southeast by his compass, which pointed toward the magnetic north pole. At most points, however, the north-seeking end of the compass needle points either east or west of true north.

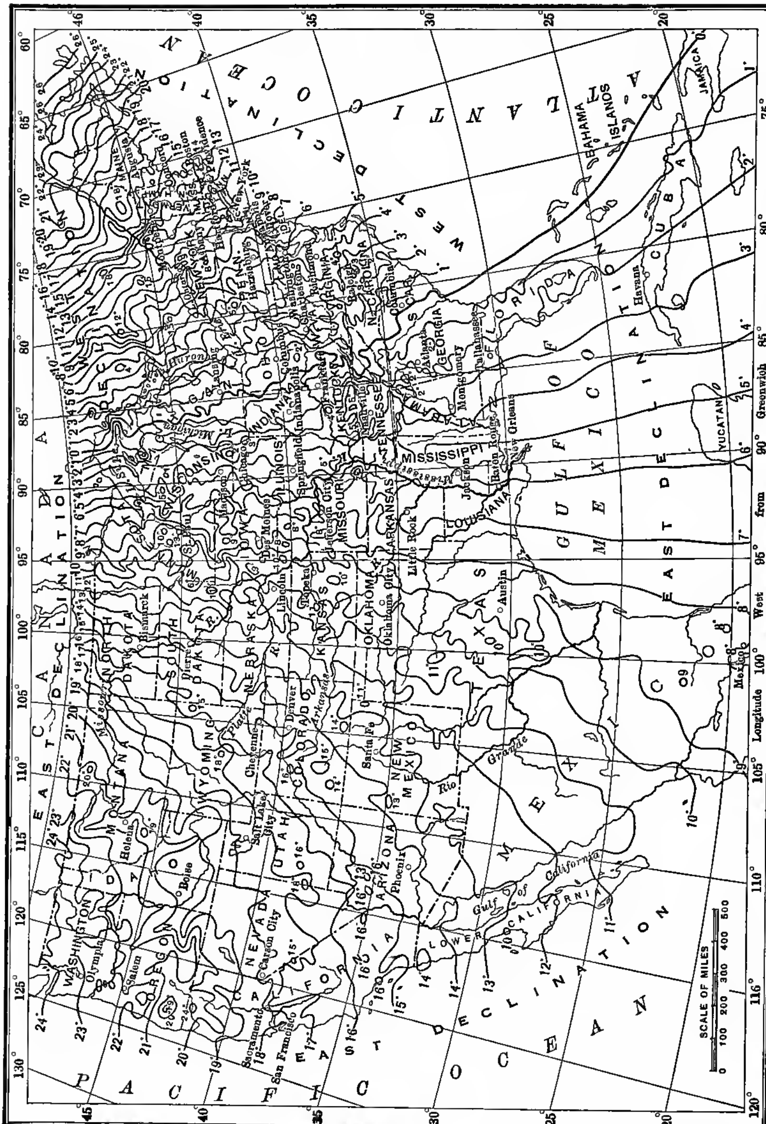
Isogonic Maps. — Figure 386 is a map of United States which indicates the directions in which the compass pointed in different parts of the country in the year 1910.

The heavy line on the map marked 0° goes through those places at which the compass needle points true. Along this line the compass would show no variation from due north; it is called the *agonic line*. There are places of no compass variation or *declination* from Lake Superior to South Carolina, points like Fort Wayne, Indiana, and Savannah, Ga. Because of what is known as secular change, the compass points due north at those places only at certain times, in this case the year 1910.

East of this agonic line in United States the needle points west of true north, and the compass is said to have *west declination*, while to the west the variation is spoken of as *east declination*.

At Ithaca, N. Y., the compass needle pointed 8° west of north; at Madison, Wis., it pointed $4\frac{1}{2}°$ east of north; and at Seattle, Wash., $23\frac{1}{2}°$ east of true north. This can be determined by studying the lines on the map (Fig. 386), the variation of the compass at Madison, for example, being nearly the same as that at New Orleans to the south, but very different from that at Boston to the east and Salt Lake City to the west. These lines go through places that have equal compass variation and are called *isogonic lines*, and the map is called an *isogonic map*.

Figure 387 is an isogonic map of the world, showing the several



WILLIAMS ENGRAVING CO., N.Y.

FIG. 386. — Isogonic map of the United States in 1910. (U. S. Coast and Geodetic Survey.)

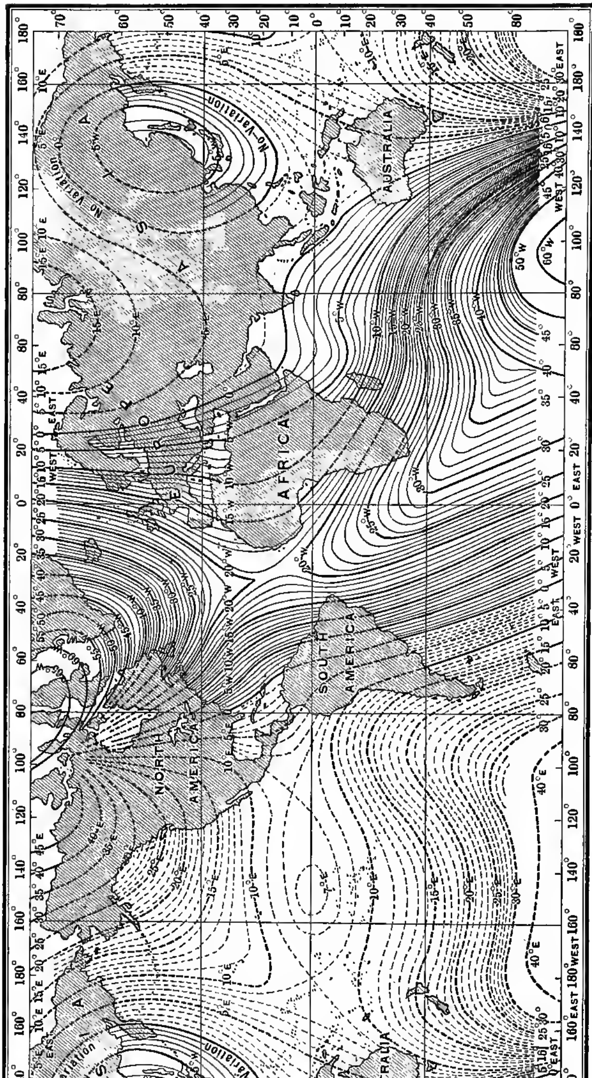
agonic lines, marked *no variation*, and the convergence of all these *magnetic meridians* toward the polar regions.

Magnetic Poles. — The place toward which the compass needle points is called a *magnetic pole*, the north magnetic pole being nearly 1400 miles from the true or geographical north pole. It is located in the Boothia Peninsula west of Hudson Bay in Canada near latitude 70° 5′ north and longitude 96° 46′ west. Its position was first determined by Sir James Clark Ross in 1831. The south magnetic pole, according to the recent Antarctic expeditions, is in the continent of Antarctica south of Australia near 71° 30′ south latitude and 153° east longitude. The two magnetic poles are not antipodal as the geographical poles are, and a line passing through the former would miss the centre of the earth by nearly 750 miles, or about $\frac{1}{5}$ of the earth's radius.

Magnetic Intensity. — The magnetic force which acts on a horizontal compass needle diminishes with approach to the magnetic poles, so that near these poles the compass is practically useless for determining directions. In consequence, also, the effect on the compass needle of irregular disturbances, called *magnetic storms*, is greater in the polar than in the equatorial regions. With the time variations in magnetic intensity there seem to be difficulties in the use of wireless telegraphy and in sending messages over telegraph wires.

Changes in Magnetic Declination, or Compass Direction. — The direction assumed by a compass needle at any one place changes with the lapse of time, as is proved by repeated observations in many parts of the world. At London the compass pointed 11° east of north in 1580, due north about 1658, $24\frac{1}{4}$° west of north in about 1812, and only $15\frac{1}{2}$° west of north in 1912. It is not possible, at present, to predict for more than about 5 years the amount of increase or decrease in magnetic declination for a given place with sufficient accuracy for the purposes of the mariner and the surveyor. The compass direction in United States ranged from 20° west to 24° east of true north in 1910, but in 1800 it only ranged from 14° west to 19° east of true north. At present the agonic line in United States seems to be shifting slowly westward. It was west of Richmond, Va., from 1750 to about 1772, and east of Richmond from 1772 to 1838, since which it has slowly travelled westward.

The Dip Needle. — Every one who uses a compass has noted that one arm of the needle is weighted. This is to make the needle remain in a horizontal position, for otherwise one end would be found to "dip" or point downward. The earth acts as a great magnet, having lines of force which extend parallel to the surface in the equatorial region and at an increasing angle with the surface as the poles are approached (Fig. 388). To these lines of force the compass needle is parallel, so that the inclination amounts, on the average, to about 75° in northern United States and increases toward the magnetic



WILLIAMS ENGRAVING CO., N.Y.

FIG. 387. — Isogonic map of the world for 1907. (Encyclopædia Britannica.)

north pole. There the end of the needle points straight down into the ground. The amount of inclination depends upon the distance from the *magnetic equator*, which is situated not far from the geographical equator. The dip is zero at the magnetic equator. To the north the dipping end of the needle is the north-pointing end, whereas south of this line, the south-pointing end of the needle dips. Always the end of the needle opposite to the dipping end is weighted. Another style of instrument, a *dipping compass*, or, more correctly, a *dip circle*, is used to measure the amount of inclination from the horizontal. This is shown by a needle so mounted as to swing freely on a horizontal axis.

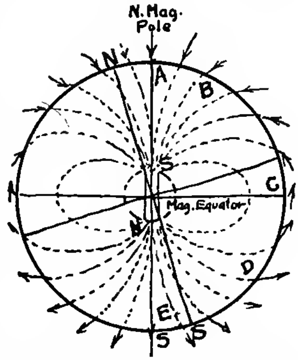


FIG. 388.—The earth as a magnet, with lines of force nearly parallel to the magnetic equator and increasing in inclination as the magnetic poles are approached. (Richardson.)

Local Magnetism. — Not only is there a field of magnetism of the earth as a whole, but there are parts of it which are locally magnetic. This is because of the presence of rocks which attract the needle; for example, certain iron ores such as magnetite. In such places the compass may be affected more largely by the local than the general magnetism, but the behaviour of the compass needle will be a balance between the influence of both. Near Juneau, Alaska, such a body of magnetic iron ore disturbs the ordinary compass needle so that it is weak and points this way and that, while the dip needle points straight down, as if it were directly over the north or south magnetic pole. Near such ore bodies, or other igneous rocks which happen to be magnetic, ships are likely to be wrecked, if corrections for local magnetism are not made. Lines of local magnetic attraction, therefore, tend to interfere with the observations of general terrestrial magnetism. By the use of the miner's dip needle or the dipping compass, iron ores are often discovered in regions where the deposit lies concealed deep beneath the surface.

Magnetic Survey of the Globe. — In recent years a very detailed study of the terrestrial magnetism of the whole earth has been undertaken under the direction of L. A. Bauer, in charge of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. In connection with this work, careful observations are being made on land and sea, in the most remote parts of the world as well as in civilized lands. For the work on the oceans a special ship had to be built, and, because of the effect of iron and steel upon the compass needle, practically all the metal parts of this ship were made of non-magnetic substances like bronze, gunmetal, and copper, the hull being wooden.

Upon this ship some very interesting and valuable observations have been made. Errors of considerable magnitude — often of a persistent nature for long stretches — have been found to exist in some parts of the magnetic charts used by mariners. In certain areas in the Indian Ocean, for example, errors in the charted compass directions amounting to 6° were found. The errors in the charted compass directions over the greater portion of the Atlantic Ocean amount to about 2°. A vessel sailing 2000 miles from San Francisco to Honolulu might be 35 miles too far north at the end of the voyage, if depending upon the older charts and not seeing the sun or stars.

Cause of Terrestrial Magnetism. — The patient gathering of data by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, by the United States Coast and Geodetic Survey, and similar bureaus in European countries, will result in vast additions to our knowledge concerning magnetism of the earth, its rate of variation, and, perhaps eventually, its cause, which as yet is unknown. It is some magnetic condition which we most commonly think of as being deep within the earth. It may be due to rotation. It may be connected with the heated interior. Its ultimate cause may even be outside the earth. At all events, the earth acts as a great magnet.

Possible Relation of Magnetism to the Aurora. — The *Aurora Borealis*, or Northern Lights, and the similar phenomenon of the

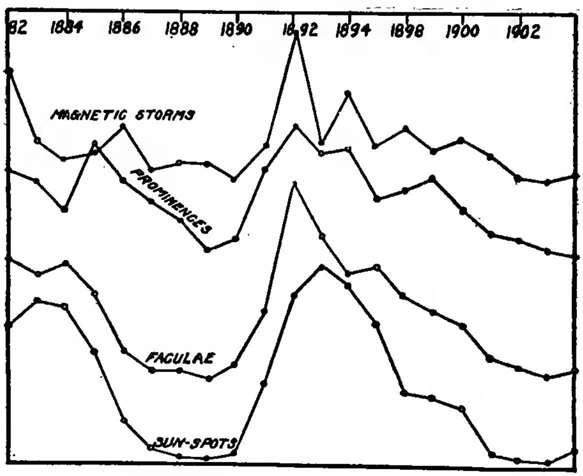


FIG. 389. — Coincidence of magnetic storms and sun spots. (Moulton.)

southern hemisphere, the *Aurora Australis*, are thought to be in some way related to terrestrial magnetism. The strange light in the northern sky, the brilliant colours, and the rapid shifting of bright streamers, which dart from horizon to zenith, are sometimes seen in winter in northern United States and are very commonly observed by polar explorers. Because the aurora is seen with greatest intensity near the magnetic poles, and because similar colours have been artificially produced by the discharge of an electric spark in a test-tube from which the air had been partially exhausted, it is thought possible that the aurora may be due to faint electrical discharges in the higher layers of the air, with some unascertained relationship to terrestrial magnetism. It is said that auroras and magnetic storms are most frequent every eleven years, and that they coincide with greatest frequency of sun spots (Fig. 389).

Importance of Terrestrial Magnetism to Man

Relation to Navigation. — Until the compass was invented, it was never possible for men to venture out of sight of land in ships, with confidence of being able to return. The compass is said to have been discovered by the Chinese as early as 1100 B.C., but it was not introduced in Europe until the twelfth century A.D. Upon the use of this instrument depends all of our commerce upon the seas. Columbus is thought by some to have been the first to note that the compass does not point to the true north and that the amount of divergence varies from place to place.

Unless we know the amount and rate of change of the compass direction we cannot safely use the compass in navigation. Along the coast of southeastern Alaska, for example, the compass pointed $30\frac{1}{2}°$ east of true north in 1910. In sailing from Alaska to Seattle or San Francisco, a ship might be some distance west of California toward the Hawaiian Islands if the variation of the compass were not known and corrected.

Relation to Exploration, Surveying, and Map Making. — The use of the small pocket compass as a guide in going through a strange country or in the woods, or in travelling on a cloudy day or at night when the sun is invisible, is of great importance to man.

The use of the compass by surveyors is at the basis of all our laying out of lands and the making of maps. It is for this reason that we must know exactly how much east or west of north the compass points. The determination of directions, the so-called points of the compass, are not always conveniently made by the true north shadow of a post or tree at noon or the observation of *Polaris*, the North Star, at night. Even if maps were made upon the basis of the present compass declination, with corrections for local magnetism, due to substances in the earth, or for the presence of iron in buildings, we should still need the precise determination of the yearly amount of change in our isogonic lines, as in a case where a boundary line might be in dispute or any other artificial line established by man with the use of the surveyor's compass.

REFERENCES TO LITERATURE

L. A. Bauer. United States Magnetic Declination Tables and Principal Facts Relating to the Earth's Magnetism, Washington, 1902; United States Magnetic Tables and Magnetic Charts for 1905, Department of Commerce and Labor, Coast and Geodetic Survey, Washington, 1908; Terrestrial Magnetism, A Consistent Theory of the Origin of the Earth's Magnetic Field, Journ. Wash. Acad. Sci., Vol. 3, 1913, pp. 1–7; The Magnetic Survey Yacht "Carnegie" and her Work, Terrestrial Magnetism and Atmospheric Electricity, Vol. 14, 1909, pp. 57–66.

Charles Chree. Terrestrial Magnetism, Encyclopædia Britannica, 11th edition, Vol. 17, 1911, pp. 353–385.

A. Nippoldt. Erdmagnetismus, Erdstrom, und Polarlicht, Leipzig, 1912, 143 pp.

Terrestrial Magnetism and Atmospheric Electricity, an International Quarterly Journal, the Johns Hopkins Press, Baltimore, Md.

PART II. THE HYDROSPHERE

CHAPTER XIX

THE OCEAN

Oceanography as a Science

The Content of Oceanography. — The scientific study of the oceans is known as *Oceanography*. This comprehensive science considers (1) the distribution and depth of oceanic waters, (2) the composition of the water, (3) its colour, (4) its temperature, (5) its movements, (6) the relation of organic life to its environment, (7) the topography and other conditions on the ocean bottom.

Former Beliefs of Deep Sea Conditions. — Oceanographic study received a great impetus when it was found that the ocean bottom was inhabited by life and that there was a great world, hitherto unknown, inviting exploration. Before that time it was supposed that the deep sea was a vast desert, incapable of supporting life because of its utter darkness and the enormous pressures that the column of water exerted in great depths. Reports that animals were drawn to the surface from great depths were received with incredulity; but when oceanic cables were laid, and, upon being drawn to the surface, were found to have animals fastened upon them, there could be no escape from the conclusion that the ocean bottom was inhabited.

Explorations by the *Challenger* and Other Ships. — Expeditions were fitted out to explore this new world, and a wealth of scientific information was gathered, not only regarding the deep sea, but upon other phases of oceanography as well. This material, added to that which was previously known regarding the oceans, and supplemented by other later investigations, have given us a fairly full knowledge regarding the general features and conditions in the hydrosphere.

Among these expeditions the one most noted was that of the *Challenger*, a ship sent out by the British government between 1872 and 1876, which made comprehensive explorations during a journey around the world. The extensive series of reports of this expedition, including the writings, here and elsewhere, of Sir John Murray, are to this day the most valuable source of knowledge concerning the oceans.

There have been many other, less pretentious expeditions which have, however, contributed greatly to the science of oceanography. Among these are several other British expeditions, including Antarctic expeditions, the German expeditions in the *Gazelle* in 1874–1876, the series of Norwegian expeditions in the North Atlantic in the *Michael Sars*, and the long-continued work of the Prince of Monaco in the *Hirondelle* and other yachts.

Knowledge concerning the conditions in the Arctic was obtained by Nansen in the *Fram*, and Peary has added some data during his expeditions.

The United States has carried on extensive oceanographic work, especially near the American coast, the work of Alexander Agassiz and many others in the *Blake*, the *Fish Hawk*, and *Albatross* being the most valuable. Maury's early work on "The Physical Geography of the Sea" is a classic. Much data has also been gathered in connection with the laying of oceanic cables.

Methods of Oceanographic Study

Most Detailed Work near Coasts. — Naturally the most thorough oceanographic work has been carried on along the coast lines of the leading nations, where the shores are accurately charted, the depths of the water determined in great detail, characteristics of the tide thoroughly worked out, and the distribution of life understood. In the open ocean and along the more remote coasts less is known. The study of the deeper parts of the ocean is far more difficult than the study of the coast, and, for this work, especially constructed apparatus is needed.

Sounding. — One of the principal instruments employed is the sounding machine, by which the depth is determined. Attached to the sounding line are thermometers which automatically record the temperature at the bottom; and others, attached at various intervals, record the temperature at different depths. Samples of water are also brought up in metal tubes, which become automatically closed when the apparatus is drawn up; and samples of the ocean bottom deposits are obtained by means of soap or other sticky substance on the end of the sounding apparatus. Even photographic exposure is made in order to determine the amount of light which penetrates to different depths. In the great depths of the ocean a single sounding may require an hour or two, but by it much information is obtained concerning conditions from the surface to the bottom of the sea.

Dredging. — Following this, a dredge may be lowered to the bottom and dragged over it, in order to secure animals and samples of the deposits on the sea floor. There are various forms of dredge, one of them being the deep sea trawl, which consists of a long, rectangular iron frame with a bag net attached. Dragged over the ocean bottom, the frame scoops up the loose deposits, and this, together with animal life, passes into the open mouth of the net, in which it may be drawn to the surface.

Tow nets are dragged over the surface to capture the forms of life there; and others are dragged at various depths to determine the nature of life between the surface and the sea bottom. The temperature of the surface water, its composition and specific gravity, and its movements are also studied.

Altogether, therefore, a vast amount of knowledge has been obtained with regard to the oceans, not alone along the coasts and at the surface, but also at the bottom and in intermediate depths.

Extent of the Ocean

Nearly three-fourths of the earth's surface is covered by the ocean waters, with an average depth of 12,000 to 15,000 feet (Fig. 390). It fills the great ocean basins and overflows the continent edges over an area of about 10,000,000 square miles. There is so much water that, as already stated, if the earth were planed to perfectly regular form, it

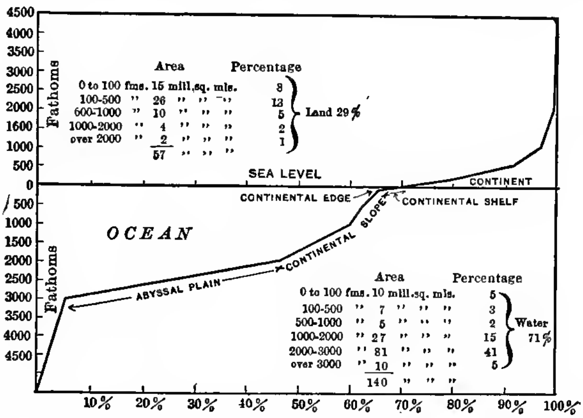


Fig. 390. — Diagram showing proportions of the ocean at various depths. (Murray.)

would be covered by a universal ocean nearly two miles in depth. Yet, compared with the lithosphere as a whole, it is a mere surface film.

The main facts about the distribution of ocean water have already been stated. From a broad belt in the southern hemisphere it extends northward between the continents, with which it is in contact along an exceedingly irregular line with many partly enclosed branches. Along this contact zone there is great activity of wave and tidal work giving rise to complicated shoreline phenomena, already studied (Chap. XI). The oceans cover over 139 million square miles.

Ocean	Atlantic[1]	Pacific[2]	Indian
Area in Square Miles	41,321,000	68,634,000	29,340,000

[1] Including Arctic Ocean, Mediterranean Sea, etc.
[2] Antarctic or Southern Ocean divided between the Atlantic, Indian, and Pacific.

THE OCEAN SURFACE

The surface of the oceans consists of saline water, varying considerably in composition and density, in temperature, and in colour, and disturbed by waves, tides, and currents.

Curvature of Sea Level. — This surface, so level as compared to the lands that it is commonly called the *sea level*, is really a curved surface (Fig. 392) conforming to the oblate spheroid form of the earth. It departs somewhat from this perfect form because, in addition to the main attraction of gravity which holds the water in place, there is a lateral attraction from the lands which border the oceans.

Distortion near Mountains. — The extent to which the ocean is distorted from the spheroidal form depends upon (1) the mass of land, (2) the density; and calculations of the amount of distortion vary because of the uncertainty of these factors, especially the second.

It has been estimated that the lateral attraction exerted by the Himalayas causes the surface of the ocean to be 300 feet higher at the head of the Bay of Bengal than at the southern end of the Indian peninsula, meaning, of course, that the water is 300 feet farther from the earth's centre in the former than in the latter place. In the same way the Atlantic water along the coast of North and South America must be nearer the earth's centre than that on the Pacific coast where lofty mountains rise. These variations in the sea level are of course liable to change, as mountains rise higher or are worn lower by denudation. This is doubtless one cause for changes of relative level of land and sea during past geological ages.

TOPOGRAPHY OF THE OCEAN BOTTOM

The general topographic features of the ocean floor (Fig. 391) have already been stated in the study of the lithosphere. In general, these are (1) a continental shelf of varying width fringing the continents, (2) a continental slope descending to the ocean basins, (3) broad expanses of plains smoothed by deposit, (4) linear elevations, some ridge-like, others broad swells, others plateau-like, (5) cliffs due to faulting, (6) volcanic cones, (7) depressions, usually linear, known as *deeps*. The nature of these features may be more fully understood by a somewhat detailed description of one ocean, the Atlantic.

THE ATLANTIC OCEAN

The Continental Shelf. — Extending eastward to a varying distance from the coast line of United States, is a fairly level, submerged plain, broadest off Newfoundland, and sloping seaward at an average rate of 1 or 2 feet per mile. This continental slope is somewhat diversified by elevations and depressions, some of the former rising up to or nearly to the surface near the coast, forming banks, shoals, or islands. The depressions are linear valleys. On the opposite side of the Atlantic, on the European coast, there is a corresponding continental shelf with similar characteristics.

It is inferred that this extension of the continental plateau is really a former land surface, worn to low relief and now submerged. This

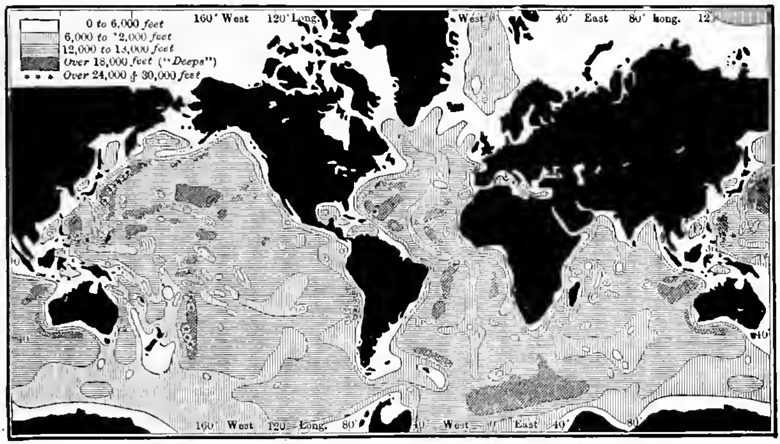


FIG. 391. — Map showing depths of the ocean. (Murray.)

inference finds support, (1) from the resemblance of the submerged topography to that of the neighbouring land, (2) from the evidence that the land has been recently lowered in its relation to the sea, (3) from the presence, on the continental shelf, of valleys, which are apparently continuous with existing and valleys. Thus, off the mouth of the Hudson River, there is a valley extending clear to the

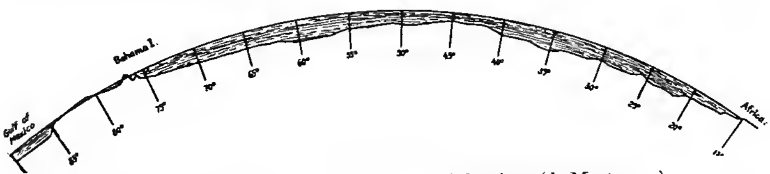


FIG. 392. — Cross-section of the north Atlantic. (de Martonne.)

edge of the continental shelf, where it forms a canyon some 2400 feet deep. Other similar, though less pronounced, valleys are found on the continental shelf off the mouths of the Delaware and Susquehanna rivers; and a pronounced valley has been traced off the mouth of the St. Lawrence. Similar submerged valleys cross the continental shelf on the European coast, notably in the North Sea.

The Continental Slope. — On each side of the Atlantic the slope increases decidedly on the outer edge of the continental shelf, and there is a descent to the ocean basins (Fig. 393). This continental slope is not to be thought of as precipitous, though it may be locally. It is usually not even a steep slope, for the descent of a mile or two ver-

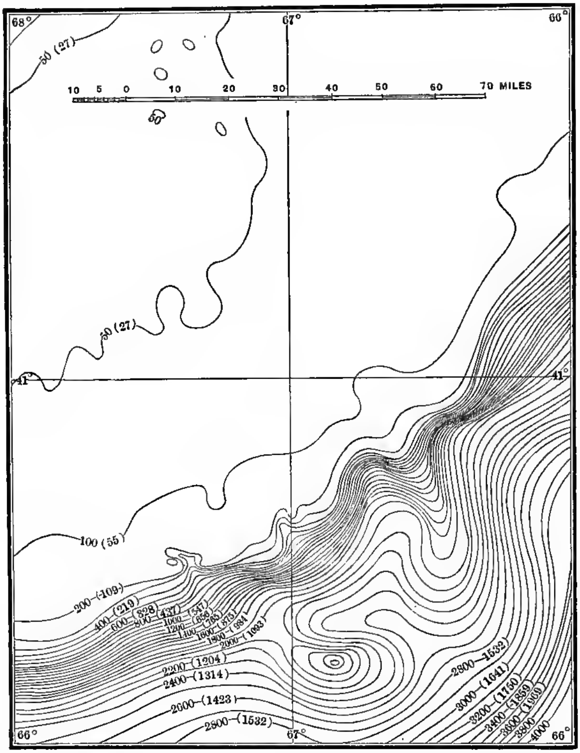


FIG. 393. — Topographic map of the steep continental slope in the Atlantic east of Massachusetts with the relatively smooth continental shelf to the northwest. Depths in metres and in fathoms, *i.e.*, 200 (109), meaning 200 metres = 109 fathoms = 654 feet. (From Boston Sheet, North K 19, International Map of the World on the scale of 1 : 1,000,000.)

tically may be distributed through a space of 50 to 100 miles. Yet, as the slopes on the ocean floor go, this continental slope is unusual, and it is striking in character because it completely encloses the oceanic depression.

The Ocean Bottom Plain and Mid-Atlantic Ridge. — At the base of the continental slope the grade flattens again, and there stretches out a vast plain which extends throughout most of the Atlantic Ocean. About midway across the ocean the bottom rises in a broad swell, or plateau, which extends the length of the Atlantic, winding roughly parallel to the enclosing continents. Its elevation varies, being covered usually by several thousand feet of water. It is sometimes called the Mid-Atlantic Ridge, but is really a series of three plateaus, varying

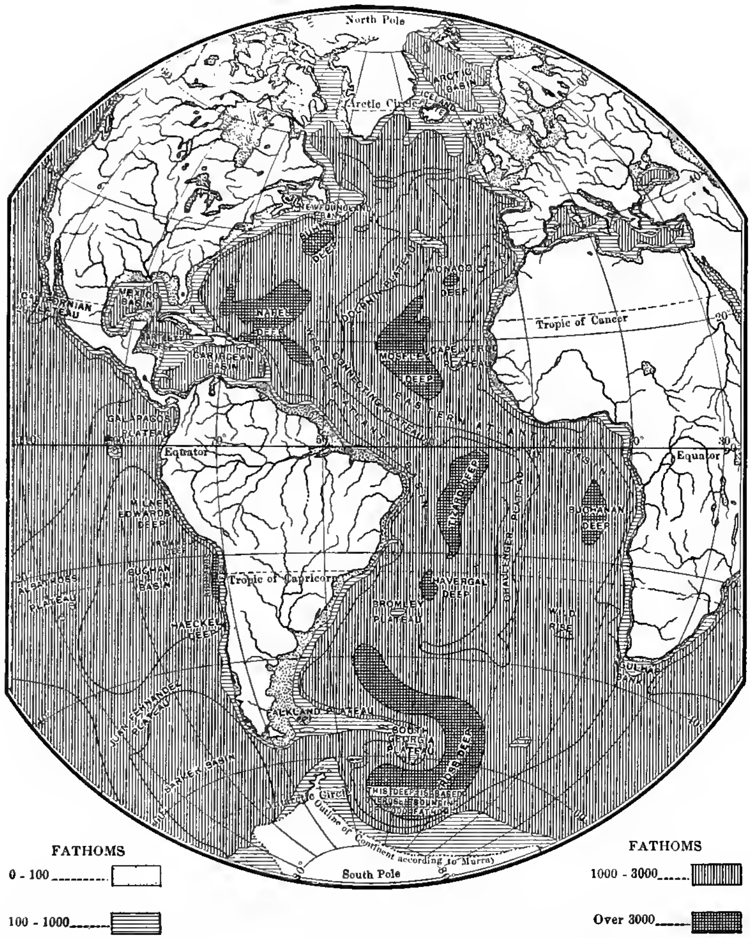


FIG. 394. — Map showing depths in Atlantic Ocean. The Mid-Atlantic Ridge is made up of the Dolphin, Challenger, and Connecting Plateaus. The continental shelves are stippled. (Challenger Reports.)

in breadth and elevation, forming an elevation not far from the mid-Atlantic. Both to the east and west of this linear series of plateaus the water is deep, being usually 15,000 to 18,000 feet, and in several areas descending in the so-called deeps to 20,000 feet or more (Fig. 394).

Oceanic Volcanoes. — Some volcanoes rise from the mid-Atlantic plateau. Iceland lies near its northern end; the Azores form a chain extending part way across it; and farther south are the volcanic islands of St. Paul, Ascension, and Tristan da Cunha. Other volcanoes rise from the deeper waters on either side of the plateau, such as the Cape Verde Islands and St. Helena on the eastern side and the Bermuda Islands on the west.

Relationship of Mediterranean Seas. — Both the Mediterranean Sea and the Caribbean-Gulf of Mexico enclosed sea really occupy basins within the continental area, the former more so than the latter. The West Indian mountain chain rises as a barrier between the American mediterranean and the ocean basin, and on the outer base of this barrier, close by Porto Rico, is the deepest known point in the Atlantic Ocean, 27,972 feet, in a linear trough known as the Nares Deep. In the West Indian mountain area and in the Mediterranean there are some very steep submarine slopes, some of them being lofty precipices. The Mediterranean has a maximum depth of 14,400 feet, the Gulf of Mexico of 12,480 feet, and the Caribbean of 20,568 feet. Since each of these seas is separated from the ocean basin by an elevation, they are really separate basins, though continuous with the ocean at and near the surface. The lowest point at the entrance to the Mediterranean is 1500 feet, the lowest point in the rim of the American mediterranean being 5400 feet.

Other Irregularities. — With the exception of a few broad indentations, such as Davis Strait, the Bay of Biscay, and the Gulf of Guinea, the other irregularities of the Atlantic border are all located on the continental shelf. The Arctic Ocean resembles the mediterranean seas in that it is a basin surrounded either by land or by relatively shallow water. Much of its area is on the continental shelf of North America and Eurasia, but in the polar portions depths as great as 14,400 feet have been found by Nansen and Peary (Fig. 379).

Other Oceans

In each of the other oceans the topography of the ocean bottom is similar in general features to that of the Atlantic. That is to say, there is a fringing continental shelf terminated by a continental slope along each of the continents, but varying greatly in width. Beyond this is the great ocean basin with level floor in the main, but diversified by both elevations and depressions similar to those described in the Atlantic. In none of the other oceans is there a medial plateau, as in the Atlantic, but there are numerous plateau areas, often with volcanic peaks rising from the crest. The topography of the western Pacific is particularly diversified by plateau uplifts, linear mountain chains, volcanic cones, and deeps (Fig. 391).

The general topography of the ocean bottoms is indicated on the accompanying maps, and will not be described in detail. The Pacific is the deepest of the oceans, having an average depth of 2¾ miles as compared with the average depth of the oceans as a whole, which is about 2¼ miles. The Atlantic is slightly deeper than the average (about 2½ miles), and the Indian Ocean is about the average depth. Not only is the Pacific deeper on the average, but it includes the greatest known oceanic depths — the Planet Deep, 32,114 feet, near the Philippine Islands, 31,614 feet near Guam, 30,930 feet near New Zealand, 27,930 feet near the Kurile Islands, all in linear deeps close by pronounced uplifts. All together there are known to be 57 deeps in over 3 miles of water, 11 in over 4 miles, and at least 5 in which the water is over 5 miles deep.

Origin of the Topographic Forms

The Three Processes. — We cannot study the topography of the ocean bottom as we can that of the land, and hence the details of topographic form are not so well known, nor can we bring so many facts to bear upon the interpretation of this form. In general, the topography of the ocean floor is clearly the result of either (*a*) diastrophism, (*b*) vulcanism, (*c*) deposition, or a combination of these. The only known exception is on the continental shelf near the continents, where there are erosional forms, now submerged. None of the oceanic agencies have erosional power, excepting in shallow water and along continental margins.

Vulcanism in the Ocean. — Forms due to vulcanism abound in the ocean. Many of the volcanic cones rise above sea level, both along the continent borders and in the open oceans; but many others are known which rise only part way to the surface. Whether there are submarine lava plateaus and other forms of volcanic deposit, is not known.

Submarine Diastrophism. — Diastrophism has played a far more important rôle in the development of the ocean bottom topography than vulcanism. The great ocean basins are themselves depressed areas, and the continental slope is apparently in the main either a line of faulting or of warping, probably in some places faulting, in others warping. The broad ocean bottom plateaus are evidently unwarped portions of the sea floor, the submarine mountain ranges are more sharply folded and faulted zones, and the deeps are areas of exceptional subsidence. Movements such as have produced these features are evidently still in progress on the ocean bottom.

Marine Deposition. — Deposition is in progress all over the sea floor, but in the deeper ocean, far from land, it is evidently very slow and is hardly a factor of prime importance in determining the general levelness. Near the continents, especially on the continental shelves, on the other hand, the waste of the land is strewn over the sea floor in an extensive sheet. Much of the levelness of the continental shelf is, without doubt, due to this deposit; and it is possible that the shelf itself is in part built by deposit from the waste of the land. Even the continental shelf may in places represent the outward advance of the deposit borne to the sea from the waste of the land.

Deposits on the Ocean Floor

The Three Types of Deposits. — In sounding, small samples of the ocean bottom deposits are commonly obtained; and in dredging larger quantities are brought to the surface. There is, therefore, fairly extensive knowledge of the materials covering the ocean bed. The nature of these materials varies with the distance from the land and with depth. These differences may best be understood by a description of three zones: (1) the continent borders, the seat of land-derived deposits; (2) the ocean basins, down to depths of 12,000 to 15,000

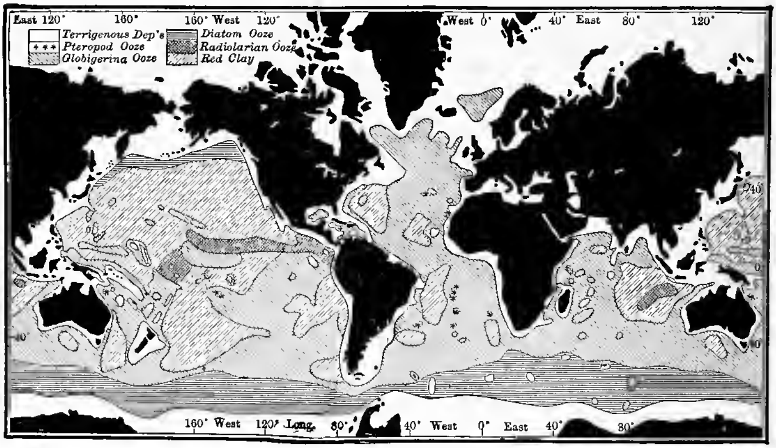


Fig. 395. — Distribution of deep sea deposits. (Murray.)

feet, over which oozes are deposited; (3) the deeper parts of the ocean basins, below 12,000 to 15,000 feet, over which red clay occurs (Fig. 395).

Land-derived Deposits. — As might be expected from their origin, the most notable characteristic of the deposits along the continental borders is their variability. These *littoral deposits* vary in texture, from gravels and sands near the shore to exceedingly fine muds offshore. They also vary in composition (1) according to the abundance of included organic remains from organic life, (2) according to the nature of material supplied from the land. Thus, in the first direction the sediments may vary from almost pure organic matter to clastic fragments nearly free from organic remains. In the second direction there is great variation, depending upon the rocks along the shore, and the nature of the sediment brought to the sea by rivers. Thus the littoral deposits may be calcareous where derived from limestone regions, or they may be made up of detritus of granitic, or volcanic, or any other of the many rocks of the land. Soundings in the zone of littoral deposits thus reveal great diversity both in texture and in composition (Pl. VI).

Ocean Bottom Oozes. — This contrasts very strikingly with the comparative uniformity of conditions in the area of the ocean bottom covered by the deep sea *oozes*. . Here, over an area equal to more than a third of the ocean bottom, over 50 million square miles, the ocean floor is covered by an exceedingly fine-grained, calcareous ooze, composed mainly of the remains of organisms that have lived in the waters of the ocean, and, upon death, have fallen to the sea bottom. Mixed with this organic matter are (*a*) remains of ocean bottom animals, (*b*) volcanic material, especially bits of pumice that have floated on the ocean and fallen to the bottom on becoming water-soaked, (*c*) minute quantities of fine-grained rock fragments from the land, (*d*) some chemical deposits, (*e*) particles of iron derived from the fall of meteorites.

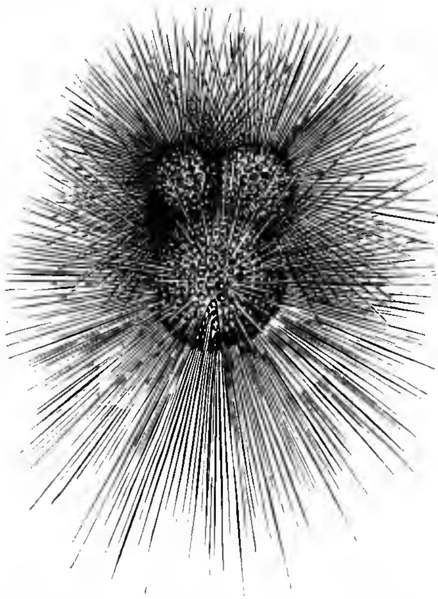


Fig. 396. — Globigerina from the surface of the ocean, much enlarged. (Challenger Reports.)

In the main the deposit is composed of the remains of minute and even microscopic organisms that live in vast numbers in the waters at the surface and at intermediate depths. Some of these are perfect in form, but many are comminuted by the action of ocean bottom animals through whose digestive tracts the ooze has passed. In the deeper waters the organic remains have suffered also from solution in the deep sea water. There is great variety in the organic remains, but over large areas the predominant forms are *Foraminifera*, particularly various species of *Globigerina* (Figs. 396, 397). This has given rise to the name *globigerina ooze* applied to these calcareous deposits of the deep sea. It is estimated that the deposit of globigerina ooze covers an area of 47,752,000 square miles at a mean depth of al 12,000 feet. In colour the ooze is commonly pale gray, thoug times coloured red by iron oxides or brown by manganese.

In parts of the ocean there are oozes in which other organisms dominant, or form so large a proportion as to give rise to other na These are, for instance, *pteropod oozes* and silicious oozes, especi *radiolarian* and *d maceous oozes.* In cases the origin is same, the differ being in the percen of certain types of ganisms. Even in ooze bearing a cer name, as globiger there are remains other organisms, s as pteropod, radiol etc.

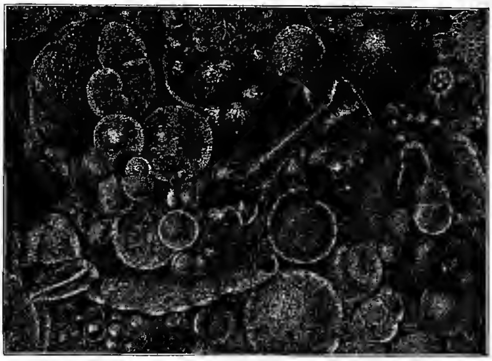


FIG. 397. — Globigerina ooze from the bottom of the sea. (Challenger Reports.)

Red Clay. — Ove area even greater t that occupied by gl gerina ooze, estim to cover some 55,000,000 square miles, or nearly that of the of the lands, is a peculiar clay, usually red in colour because of stain, though sometimes chocolate because of manganese stain. *red clay* deposit, which occupies the deeper parts of the ocean depths below 12,000 to 15,000 feet, is the most extensive deposi the earth, as well as one of the most slowly forming.

In it there are remains of organisms which have lived in the wa above, but only these which are sufficiently insoluble to have resi

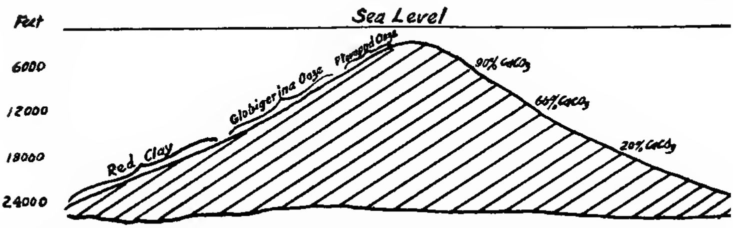


FIG. 398. — The relations of distribution of ooze and red clay to depth, shown on th and the decreasing proportion of lime in the latter, on the right. (Murray.)

the solvent action of the deep sea water, which is charged with ca dioxide. Calcareous remains and other soluble substances are solved in passage through the deeper waters, and only their insol residue passes on to the bottom (Fig. 398), making minute contribut to the sediment. Grains of volcanic materials and bits of pumice also constitute a part of this peculiar sediment. How slowly the red clay is accumulating is indicated by the fact that the silicious ear bones of whales and teeth of sharks are frequently drawn up in dredgings in the red clay area far from land. Since few such animals would fall to the bottom in any one locality in a brief interval of time, the fact that small parts of such animals are brought up in the dredges is clear proof of the great slowness of accumulation of the red clay. Even more striking is the fact that particles of metallic iron are also found in dredging in these great depths. These iron particles are evidently portions of meteorites which have fallen into the sea. One would need to make a careful and long extended search on the land to find even one of these fragments; but the deep sea dredgings, located by chance, have frequently brought them to the surface. Since it cannot be inferred that such material falls more abundantly in these areas than on the land, we must conclude that their abundance is the result of concentration through centuries in an area of such slight deposit that they are not deeply buried.

The iron and manganese which discolour the deep sea clay are derived from the insoluble residue of the marine organisms, from the volcanic minerals, and from the cosmic iron particles. Oxidized in the impure waters of the deep sea, the iron assumes the strong red colour which gives the name to the red clay.

Absence of Deep Sea Sediments on Land. — It is a noteworthy fact that, though the red clay covers an area greater than that of the lands, it is not recognized among the sediments of the continents. Even oozes, covering nearly as great an area, are not conspicuous among the sedimentary strata of the land, the chalk deposits — a variety of limestone — found in a few places being the sole exceptions.

From these facts one is forced to the conclusion that, although portions of the continents have again and again been lowered beneath the sea, now here, now there, such depressions have rarely extended far enough to introduce real deep sea conditions; and never, so far as we know, have any parts of the existing continents been lowered to the depth where red clay was deposited. Whether this is an argument for relative permanence of ocean basin and continent plateau position, or whether it is merely an indication that in earlier ages deep sea conditions did not exist, cannot at present be stated. It is of course also possible that parts of continent areas have actually been depressed to deep sea conditions and have then remained there.

Conditions on the Ocean Bottom

Uniformity and Monotony. — There is no part of the earth's surface where there is such uniformity of conditions and such monotony as on the deep sea bottom. No sunlight penetrates to these great depths, and a condition of perpetual darkness prevails there, excepting as relieved by the phosphorescent light emitted by deep sea animals. The differences between day and night and summer and winter, therefore, produce no effects on the ocean bottom.

Without sunlight there can be no plant life; but animal life exists in considerable variety, depending for its food supply upon that which rains down from above, as organisms in the upper levels of the ocean die and fall to the bottom.

The Great Pressure. — Since the pressure increases from $1\frac{1}{5}$ tons to the square inch in 6000 feet to $6\frac{2}{5}$ tons per square inch in the deepest water, it is clear that the deep sea animals live under an enormous pressure. The superincumbent water has no noticeable effects, since the pressure, being equal in all directions, is counterbalanced in all parts of their bodies. Only when the deep sea forms are raised to the lighter pressures of the atmosphere are the effects of these deep sea pressure conditions noticed. Then, with pressure removed from outside, expansion of gases within causes their air bladders to protrude from the mouth, their eyes to project from their sockets, and their skins to crack open.

Coldness. — Besides darkness and great pressure, the ocean bottom is perpetually cold. The temperature of the ocean water in general decreases with depth, and, throughout most of the deep ocean basins, is within four degrees of the freezing point, and in places even below the freezing point of fresh water. Such uniformly low temperatures naturally reduce the vitality and diminish the variety and abundance of deep sea life, especially in the deeper, colder portions.

Slight Movement. — In the deep sea there are no rapid movements of the water, such as one finds on the surface and along the ocean margins, but there is a very slow current, or drift, by which the low temperatures are imported. This drift is also the source of the oxygen which the deep sea life must have, but in the deeper waters, far from land, it is not sufficient to bear away the carbon dioxide. In such places the bottom water is so charged with these gases that it performs the solvent work already referred to in describing the red clay deposits.

Uniform high pressure and cold characterize the bottom of the great ocean basins. In addition to the lack of variation with the seasons, or with day and night, there is no diversity of conditions due to movements of the oceanic waters. Far and wide is a broad expanse of ooze or clay, and the only change is that which is caused by the slow rain of organic remains from above, — the source of the food supply, — and the slow drift of the cold waters, — the source of the oxygen supply, of the deep sea animals.

Composition of the Ocean Water

Amount of Mineral Matter in the Sea. — The waters of the ocean differ from those of the land in being salt. But, besides common salt, there are a great number of substances dissolved in the ocean water. Altogether there are about 3½ parts of dissolved mineral matter to every 100 parts of ocean water. In other words, there are 3½ tons of dissolved mineral in every hundred tons of water. Altogether the oceans contain about 5⅘ million cubic yards of dissolved material; 4½ million cubic yards of this is common salt. If all this material could be removed and deposited in a uniform layer, it would form a layer 175 feet thick over the entire ocean bottom. There is fully ⅕ as much mineral substance in solution in the oceans as exists in the lands above sea level. It is this dissolved mineral that causes ocean water to be heavier than fresh water. Taking the specific gravity of fresh water as 1, that of sea water is, on the average, 1.026.

Substances Present. — Among mineral substances dissolved in the ocean, common salt, or sodium chloride, is by far the most abundant, constituting 77.758 per cent, or more than two-thirds of the whole. Then follow magnesium chloride (10.878 %), sulphate of magnesium (4.737 %), sulphate of lime (3.6 %), sulphate of potash (2.465 %), carbonate of lime (0.345 %), and bromide of magnesium (0.217 %). A complete analysis, while doubtless revealing the same order of importance, would give slightly different percentages, for a great variety of substances are in solution in the ocean in even more minute quantities. No less than 32 different elements have been detected in sea water, and there is little doubt that all the elements in the rocks of the earth's crust exist in some combination or combinations in sea water. Among the elements known to exist in solution in the ocean water are gold, silver, copper, zinc, lead, cobalt, nickel, manganese, aluminum, iron, and silicon.

Source of Salts in the Sea. — The source of these salts is not far to seek. While some are doubtless supplied during submarine volcanic eruption, certainly a large proportion of them reach the sea in solution in the fresh water of the lands. Through the complex processes of rock disintegration and the chemical changes caused by underground water, a mineral load is supplied to running water which finds its way to the sea. That this source is capable of causing salinity, and the concentration of other mineral substances in water where there is concentration through evaporation, has already been pointed out (p. 324) in connection with the development of salt lakes.

The present chemical impurity of the ocean water could readily be accounted for on the simple assumption that through the geological ages the waste of the land has supplied this mineral load, the water evaporating as fresh water vapour from the surface of the sea, passing over the land and bearing a load of dissolved mineral matter, and later passing through a similar cycle on again being exposed to evaporation.

Indeed, on the assumption of an original fresh water body, growing progressively salter, an attempt has been made to estimate the age of the ocean, with the result of about 370,000,000 years. Such a calculation can have no certain value; because (1) it is not certain that the original ocean was fresh; (2) the volume of the ocean may have varied widely during geological time; (3) the possible supply of sodium chloride from other sources than rivers of the land is of unknown quantity; (4) extensive quantities of salt once in the ocean have been taken from it during the deposit of sedimentary rocks, in which there are even beds of salt.

Contrast with Salts in Rivers. — The fact that the salts in the ocean water are not in the same proportion as those in the running water of the lands might seem opposed to the view of land origin of mineral water in the sea. For example, carbonate of lime forms a very common and easily recognized constituent of fresh water, while sodium chloride is present only in minute quantities. Silica, commonly present in fresh water, is present in salt water only in minute quantity; and, on the other hand, the most abundant salts in the ocean (the chlorides, sulphates, and bromides) are not common either in the rocks of the land or in running water.

Withdrawal of Lime and Silica. — The excessive amounts of oceanic salts which occur only in minute quantities in fresh water is not difficult to understand as a result of concentration through constant supply from the land, and constant evaporation of ocean water. That more common substances, like silica and carbonate of lime, are not also concentrated and caused to form dominant constituents of the mineral load of the ocean waters, is evidently due principally to two facts: (1) that organisms are constantly extracting them, (2) that there is precipitation. Increase in salinity diminishes the solvent power of water for carbonate of lime, and precipitation is known to be in progress in parts of the ocean. Also there are precipitates of glauconite, manganese, and other substances on parts of the ocean bottom. A great variety of living forms with countless billions of individuals are at all times extracting carbonate of lime from sea water and building it into bones, shells, tests, and other parts of organisms, both animals and plants. Silica is likewise extracted by a great variety of animal and plant life, such as sponges, radiolaria, and diatoms. By these two processes those mineral substances which animals can use are extracted and their quantity kept down; while substances not needed in organic life are left to accumulate.

Variations in Mineral Content of Oceans. — Throughout the ocean there is a fair degree of uniformity in the mineral load, for the ocean waters are ever in movement, and there is, therefore, a tendency toward mixture. There are, however, some noteworthy variations in composition, and consequently in density. Probably there are variations near the coast, due to the composition of the waters that run off from the land; and certainly there is decrease in density where large rivers pour the lighter fresh water into the sea. Similar decrease in density is observed in oceanic areas of heavy rainfall and in the Arctic and Antarctic regions, where evaporation is slight, and where melting ice returns much fresh water to the ocean. While the average density of ocean water is 1.026, in the ice fields of the Antarctic a density of 1.024 has been observed.

On the other hand, there is increase in density in areas of evaporation, for there fresh water is removed and the salts are more concentrated. In the Trade Wind belts of the ocean, evaporation is so effective that the density of the ocean surface water is notably increased, as in the North Atlantic, where a density of 1.0278 has been observed. Even more dense is the water in seas enclosed by warm lands and shut off from free mixture with waters of the open ocean, as in the Mediterranean and Red seas. In the latter a density of 1.03 is recorded.

Since the dense water is heavier, it tends to sink, and, therefore, a limit is set to the extent to which surface water may be made dense by evaporation. This gives rise to a circulation with a tendency (1) toward mixture of waters of different densities, (2) toward the stratification of oceanic waters according to density. Were it not for other movements of oceanic waters, it is probable that such a stratification, with the densest water at the bottom, would be much more pronounced than it is. The most notable difference in density with depth are those observed where large quantities of fresh water are added to the ocean surface, as by rain, by inflow of rivers, and by melting ice. There the lighter freshened water floats on the denser salt water, and there are often very decided differences in density with depth.

There is a very common misconception to the effect that the ocean water so increases in density that, below a certain level, objects that sink in ordinary sea water will float. That this is not true, is proved by the fact that even microscopic organic remains sink to the ocean bottom, even at depths of several miles. Water is so nearly incompressible that, even under the enormous pressure of the deep sea, there is only slight increase in density as a result of the pressure. In this respect the hydrosphere is strikingly different from the atmosphere. The density of the ocean bottom water is, however, greater than that of the surfaces for a variety of reasons: (1) the settling of dense surface water; (2) a measure of compression under the weight of the overlying column, notably as a result of the compression of included gases; (3) the low temperatures, for the density increases with decrease in temperature in sea water down to 28° F., the freezing point, while in fresh water density diminishes with a fall of temperature after 7° above the freezing point is reached.

Gases in Sea Water. — Besides mineral substances, ocean water also contains large quantities of atmospheric gases in solution, nitrogen and allied inert gases in greatest amount (37½ %), oxygen next (33½ %), and then carbon dioxide (16¼ %). These are absorbed from the air on the smooth ocean surface, and in spray and foam of the wind waves. Both oxygen and carbon dioxide are also added by the marine organisms, and probably there is further supply from submarine volcanic sources. There is a limit to the amount of each of these gases that can be absorbed by the water, and this limit varies with the temperature, cold water being capable of dissolving more than warm. Thus it has been found that a little less than twice as much nitrogen and oxygen are dissolved in sea water at 32° F. than at a temperature of 86°.

Although the main supply of these gases comes from the atmosphere, and hence is absorbed at the surface, all three are found in all parts of the ocean. They are thus distributed to some extent by slow diffusion, but primarily by movements of the oceanic waters. This is a matter of very great importance, since upon the presence of the dissolved oxygen life in the ocean mainly depends, and particularly at depths below the surface. In organic processes there is constant withdrawal of oxygen from the ocean water; and, in some of the deeper parts of the ocean, animal life is limited by reason of the scarcity of this gas. Nitrogen, being little used by marine organisms, does not vary greatly. Carbon dioxide is taken from the upper layers of the ocean by plants, but since there is no plant life in the deep sea, there is no exhaustion from that source. On the contrary, organisms at the surface, on the sea floor, and in intermediate depths are contributing carbon dioxide to the sea; and in all probability there is further important contribution from submarine volcanic sources. There is no depletion of the supply of carbon dioxide; but, on the contrary, it is probable that the ocean is one of the sources of carbon dioxide in the atmosphere. It is estimated that there is 18 times as much carbon dioxide dissolved in the ocean as exists in the entire atmosphere.

Colour of the Ocean Water

Distribution of Blue and Green Water.—The normal colour of the ocean water is blue, and it is often a rich indigo blue; but in some parts of the ocean the blue colour is absent and the water is green instead. The bluest of waters are found in the warmer parts of the ocean, as in the Gulf Stream, while the colder waters, such as the Arctic, are the greenest. Green ocean water is also found along some of the coasts. The causes for the differences in colour are not thoroughly understood, and they are perhaps of somewhat complex character.

Relation to Colour of Sky.— One naturally thinks of reflection from the sky as a cause for the blueness of the ocean, and this is doubtless a factor; but the fact that the blue and even indigo blue may be seen with overcast sky, while the deep blue is not observed in the Arctic waters, even with bright sunshine, proves that this is not the sole cause.

Relation to Pureness. — Observations upon distilled water placed in a long tube show that its natural colour is blue, while the addition of organic or inorganic impurities gives a greenish colour. It seems probable, therefore, that the bluest ocean waters are the purest, while the green waters have a larger proportion of either organic or inorganic matter. The white light entering the sea water is diffracted, and the light waves of shortest length — the violets, indigoes, and blues — are scattered and reflected, giving the blue colour. With more impurity the coarser green waves are also reflected, and dominate in determining the colour.

Relation to Rivers. — Near coasts a cause for the greenish water may well be the suspended sediment that finds its way to the sea from the land. In some of the partly enclosed seas like the shallow Baltic, the water is already discoloured by sediment; and off the mouths of large, muddy streams, like the Mississippi, the sea is discoloured for long distances. It is due to this cause that the Yellow Sea of the Chinese coast received its name.

Selective scattering and reflection of certain colour waves in white light is probably the chief cause for the blue and green colour of the sea, with reflection of the sky colours as a subordinate coöperating cause for ocean water colour.

Relation to Life. — In all ocean water there is a vast abundance of minute and microscopic life; and it is possible that the difference in the nature and abundance of this life is the reason for the fact that the water is blue in one part and green in another. If such life is more abundant in cold than in warm waters, as seems to be the case, the selective scattering of the green rays may be explained. The colour of the Red Sea is said to be due to the presence of immense numbers of minute reddish algæ.

Relation to Salinity and Dissolved Gases. — There are two other possible causes for the difference, — salinity and amount of dissolved gases. The cold waters are less saline and contain more included gases than the warm waters. In shallow water, the colour is in part determined by reflection from the bottom, and in coral reef regions the reflected greens and purples from the different areas of sea bottom are often very beautiful, in the midst of the normal indigo blue.

Light in the Ocean

Depth of Penetration by Sunlight. — The sunlight becomes rapidly dimmed in its passage through water, and at great depths no sunlight penetrates. By an ingenious apparatus Helland-Hansen succeeded in exposing photographic plates during the expedition of the *Michael Sars* in 1910. He found that at depths of 300 feet during bright sunlight all the rays of the spectrum were present in sufficient quantity to affect photographic plates exposed for two hours. At 1800 feet, blue rays were present, but no sign of red and green rays; below 1800 feet and down to 3000 feet light penetrated in the form of ultra-violet rays, while rays which the human eye sees were present in only small quantity. At a depth of 5400 feet an exposure of two hours failed to show the existence of even ultra-violet rays. We may, therefore, assume total darkness for the ocean bottom at depths of a mile and over, in so far as sunlight is concerned.

Phosphorescence. — Ocean bottom animals are, however, in many cases provided with means for the production of phosphorescent light. When a dredge is brought to the surface at night, it is first seen as a glowing object, and the cold ocean bottom ooze and the animals in it are aglow with phosphorescence. A dim light is, therefore, provided, and at least some species of animals carry their own light or develop it on need.

Phosphorescence is not confined to the ocean bottom. Surface organisms, both large and small, are capable of developing it, and so probably are the animals of intermediate depth. This phosphorescence is often seen in the ocean, a boat leaving a trail of phosphorescent light, developed by the countless millions of organisms disturbed by its passage. The whole water seems aglow because of the immense number of minute organisms in it, and here and there a larger phosphorescent animal with brighter light shines out in the midst of the general glow. Such phosphorescence is wonderfully developed in the cold northern waters; and it is not always present to the same extent and degree. Some nights it is developed on the slightest disturbance of the water; at other times it is not to be seen. Neither the cause for the phosphorescence nor for its variation are understood; nor is it known what part it plays in the economy of organisms.

Ocean Temperature

The temperature of the ocean water varies notably (1) from place to place on the surface, and (2) from the surface to the bottom. While there is much irregularity, due to special causes, there is, in general, a decrease in temperature (1) from the surface downward, and (2) from equatorial to polar regions at the surface (Fig. 399).

Surface Temperatures. — In equatorial regions the average temperature of the surface waters is about 80° F., and there is a general, though not regular, decrease from this to 28°, the freezing point of salt water in the polar regions. Salt water differs from fresh water in two very important respects in connection with change in temperature: (1) while fresh water freezes at 32° F., salt water freezes at 28°, or, if its salinity is reduced, at a slightly higher temperature; (2) while fresh water ceases to grow denser and sink at 39.2° F., salt water continues to become denser and to sink until the freezing point is reached.

Water warms much more slowly than land, and it also cools more slowly, so that there is less variability in the temperature of the ocean surface from day to night and from season to season than on the lands in the same zone. Thus, both in tropical and polar zones, the annual range of temperature of the surface waters does not normally exceed 10° at any given locality. The temperature range on the frigid ocean may become notably increased when it is frozen, for then the ice surface may have a temperature far below the freezing point, though it cannot rise above it. The temperature of the water beneath the ice, however, does not decrease with that of the ice. Between the polar and tropical zones there is a greater annual range of temperature, in some places where there are cold currents in winter and warm currents in summer even amounting to as much as 40°. But even this range, which is great for the ocean, is small compared to the range on the land in the same latitude, which may amount to as much as 100° to 125°.

As soon as the temperature of the surface water changes, there is a corresponding change in its density; and, since water is a very mobile

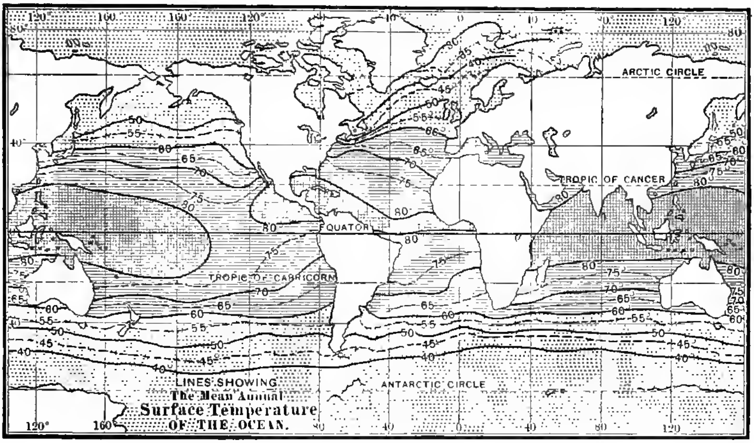


FIG. 399. — Temperature of the surface of the ocean in degrees Fahrenheit. (Challenger Reports.)

liquid, there is consequent movement in order to bring about adjustment to the new density condition. Some of this movement may be vertical, some of it in surface flow. There is thus a tendency to distribute the temperature condition of one locality to another, either horizontally or vertically. Further distribution is affected by the movements resulting from differences in density due to salinity, and by the currents of water that move before the winds. In these ways the water warmed or cooled in one latitude may transport the temperature of that latitude to another part of the ocean.

Influence of Flow on Surface Temperature. — There is a general flow of surface water in a series of well-defined currents and drifts from equatorial to temperate regions, and even into the polar zones. These warm currents bend the ocean surface isotherms distinctly northward, whereas surface currents from the polar zones bend them southward. Thus, instead of a parallel series of isotherms with regularly progressive decrease in temperature from equator to pole, we have, as the chart of the Atlantic (Fig. 399) shows, a very irregular arrangement of the ocean surface isotherms. This is the greatest cause for disturbance of the regularity of the decrease in temperature from the equator to the poles; but the influence of neighbouring lands is also important.

Influence of Land on Surface Temperature. — The influence of the lands is not important directly, but because of the water and air that flow from them. Locally the ocean water is warmed by the inflow of river water; and it is locally cooled by the discharge of icebergs from tidal glaciers. Much more general, and much more important, is the outflow of air from the land, bearing with it temperatures of the land. This influence is a cause for lowering the ocean temperature where the outflow is from glaciers or from the cold land of winter; it is a cause for raising the temperature where the winds blow from warm lands. The first influence must be felt in the partly enclosed Arctic, and in such seas as the North Sea and the Baltic. The warming influence is distinctly noticeable in the mediterranean seas of the warmer regions, such as the Gulf of Mexico, the Mediterranean, and the Red Sea, all of which have higher temperatures than the neighbouring ocean. The Red Sea is the warmest large area of the ocean water, its temperature rising to 90° and, at times, in summer, even higher. The extent to which the land exerts this influence depends upon the direction of the wind, being least noticeable on coasts toward which the prevailing winds blow, and being most noticeable on those seas that are nearly land-enclosed, like the Red Sea.

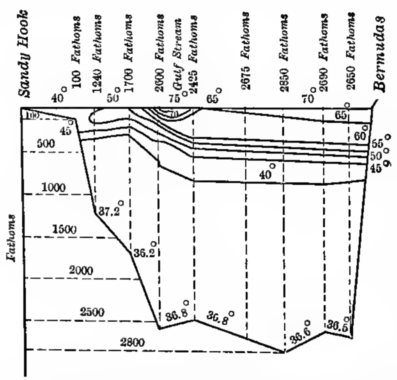


FIG. 400. — Profile of the Atlantic between New York and Bermuda, showing relations of temperature to depth. (Alexander Agassiz.)

Temperatures below the Surface. — Deep sea exploring expeditions have made great numbers of temperature observations, at various depths, in all oceans, so that the vertical range of temperature is now fairly well known (Fig. 400). These observations are made with a special form of thermometer attached at intervals to the sounding line. Provision must be made to record the temperature at a known depth, and this is accomplished by the automatic inversion of the thermometer on being drawn toward the surface, and the automatic recording of the position of the mercury at the moment of inversion. Provision must also be made against the enormous pressure in the ocean depths, which is about a ton per square inch for every 1000 feet of depth. This is accomplished by means of a protecting outer tube on which the pressure is exerted, but without pressing on the mercury bulb.

Decrease of Temperature with Depth. — In the open ocean it has been found that there is at first a rapid decrease in temperature in the temperate and tropical zones, and then a much slower decrease toward the ocean bottom, except when surface water is at freezing. Generally the temperature is below 40° F. in depths greater than 4000 feet, and it is probable that four-fifths of the water of the oceans has a temperature of 40° or less, while the average temperature of the water of the entire ocean cannot be much, if any, higher than 39°. From the 40° level, at a depth of 4000 feet or thereabouts, the temperature decreases slowly, reaching 34° to 36° in the deep ocean basins (Fig. 402), and in places, especially in the southern oceans, descending to 32° and even to 31°. Under the equator the ocean bottom temperature, at great depths, is close to the freezing point (Fig. 401).

While it cannot be said that the ocean waters are characterized by certain temperatures at given depths, there is a general stratification, with colder water at the bottom, and with the cold layers by far the thickest. There are four notable variations from this general condition. (1) On the continental shelves there are local differences due to currents and to seasonal variations. (2) In the paths of ocean currents there is often interference with the rate of decrease, and this interference may vary with the season, or with a shifting of the position of the current. (3) In the polar zones, since the surface waters are never warm, the nature of the change from surface to bottom temperature is different from that of the warmer zones. (4) Enclosed seas depart widely from the normal rate of decrease.

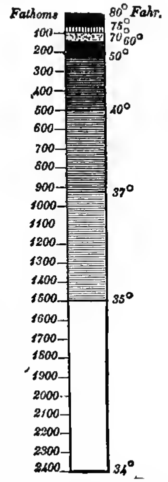


Fig. 401. — Rate of decrease in temperature at the equator.

Temperatures in Enclosed Seas. — This latter point is one of very considerable importance. In the Atlantic Ocean off Porto Rico, at a

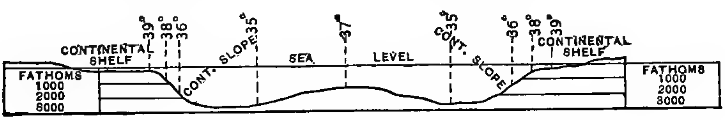


Fig. 402. — Diagram to show relation of temperature to depth in the Atlantic.

depth of 12,000 feet, the depth of the lowest portion of the Gulf of Mexico, the temperature is 35°; but the temperature at the bottom of the Gulf of Mexico is only 39½°, which is the temperature of the Atlantic water at a depth of 5400 feet. South of Porto Rico, the lowest point in the barrier of the Gulf of Mexico is 5400 feet. It appears, therefore, that the coldest water that finds its way into this enclosed sea is from this 5400 foot level, and, being denser than the rest of the water of the Gulf of Mexico, it settles to the bottom. It appears also that coldness of ocean water is not an inherent quality of depth, otherwise the bottom waters in the Gulf would have the same temperature as the ocean waters at the same depth (Fig. 403).

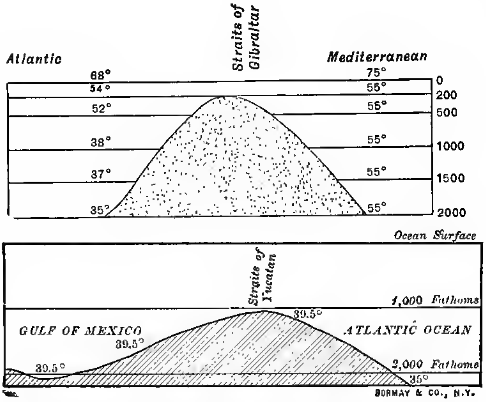


FIG. 403. — Temperatures in the Mediterranean and Gulf of Mexico controlled by the barriers at their mouths.

Other partly enclosed seas illustrate the same condition. The Mediterranean, for example, though over 14,000 feet deep, has a uniform temperature of 55° below a depth of 750 feet, while in the open Atlantic off Gibraltar the temperature is 37° or 38°. The Red Sea has a temperature of 70° from a depth of 1200 feet to its bottom, 3600 feet below the surface. On the theory that these bottom temperatures of enclosed seas are due to the creeping in of water at the level of the barriers, oceanographers have even gone so far as to predict the existence of undiscovered barriers to account for unusually high bottom temperatures, and by later soundings verified the prediction.

Coldness at Great Depths not Inherent. — The cold waters of the ocean depths cannot be an inherent condition, for there are causes present which would slowly raise the water temperature, if permitted to operate uninterruptedly. Two of these processes are of special importance: (1) heat is slowly escaping from the earth, and, as it is conducted to the ocean waters, it raises the temperature, and, since this decreases the specific gravity, the water rises. In the long geological ages this process of itself would have destroyed any inherent cold in the ocean bottom water. (2) The sun shining on the water surface raises its temperature, and, slow though the process of conduction through water is, it may be confidently stated that this cause too would have sufficed long since to raise the temperature of the bottom waters well above their present condition if no additional store of cold water were supplied.

Creeping of Cold Water toward the Equator. — There is a perfectly simple cause for this cold water and for keeping up its supply; namely, the sinking of cold water in temperate and polar zones and the creeping of this dense cold water along the ocean bottom, with a slow rise at the equatorial belt to restore the equilibrium due to the poleward surface flow of the warm ocean water. That this is the actual cause of the coldness of the ocean waters is clearly indicated by several facts: (1) near the equator, temperature records have revealed an uprise of the cold waters; (2) the coldest ocean bottom water is found in the oceans most open to the polar zones — notably the South Atlantic, the South Pacific, and in the North Atlantic on the western side, which is most open to the Arctic; (3) the temperature conditions in partly closed seas which indicate a creep of the cold ocean water; (4) the presence of oxygen in the bottom water, although living in it are animals which are using up the supply, and which would exhaust it if it were not replenished.

For these reasons it is generally believed that the cold water of the cool temperate and polar zones settles to the bottom and creeps along it in a broad, slow drift. This conclusion receives support from the Mediterranean, where in winter the water is about 55° from surface to bottom, while in summer the surface temperatures are higher. Apparently the basin is filled with the coldest water of the successive seasons, and only a surface layer is influenced by the summer temperatures. The Arctic and Antarctic bottom waters show a slight increase in temperature, due to the creeping in of cold, dense water of the cool temperate latitudes of the sixties. This dense water seems to be beneath the cold, but less dense, Arctic water.

In the Mediterranean there is also some influence from the inflow of water from the ocean through the narrow Strait of Gibraltar, but this is evidently not the dominant cause for the temperature conditions, since the water of the Atlantic at the level of the straits is slightly above 55°. The Mediterranean, therefore, on a small and simple scale, is similar to the great oceans, in being filled with water of a temperature determined by the period of greatest cold. In the oceans the conditions are more complex, for they are larger and more irregular, they extend through all the zones, and they are disturbed by a complex system of currents. They have not, therefore, and cannot reach the simple condition of the Mediterranean, which is in almost complete equilibrium in winter, but is somewhat disturbed in summer.

Ice in the Ocean

Sea Ice. — In cold temperate latitudes, ice forms on the sea in shallow waters along the coast, and especially in partly enclosed bays and harbours. In the frigid zone even the open ocean freezes over, and thus the sea surrounding the North Pole is covered with ice. Up to the point of freezing, which varies from 26° to 28° according to the salinity, the ocean water becomes denser and sinks; but with freezing there comes expansion, so that the sea ice floats. It is, however, heavier than fresh water ice, because it includes the salts that were in solution. These salts do not enter into the structure of the individual ice crystals, but are separated out from the water during freezing and are included in the ice mass as salt or brine. Therefore the sea ice is saline, as is the water from which it is frozen.

Leads and Pressure Ridges. — In the Arctic the sea ice forms to a depth of 10 feet or more, and, if undisturbed, forms a broad ice plain on which the winter snows fall, and over which it is easy to draw a sled. With the movements of the tidal and other currents, this ice plain is broken by *leads* where there is tension, and in these leads open water appears; but in the bitter cold of the Arctic winter they are soon frozen over by new ice. Where the currents cause compression, the ice is thrown into *pressure ridges* and pack ice, which may rise to a height of 50 or 100 feet, consisting of broken and upturned blocks like miniature mountains of ice. Sea ice crushes ships which are caught in it, unless especially built to evade pressure by rising, as in the case of Nansen's ship, the *Fram*.

The Arctic sea ice is a highway of winter travel for Eskimos, and it has also been followed by numerous Arctic explorers, including Peary and Nansen. The pressure ridges and the open leads are the greatest obstacles to such travel, and it was in one of the leads that Marvin lost his life on returning, during Peary's successful expedition to the North Pole. In summer, when the sun is above the heavens all the time, the surface of the sea ice melts, the ice breaks apart, and the leads no longer freeze. Travel over it is then impossible, and this is the reason why, in spite of the great cold, expeditions over the sea ice have always started near the end of the winter night, and have planned the return before the summer warmth has made the ice impassable.

Floe Ice. — Slowly drifted about and broken by melting and by movement in the currents, the Arctic sea ice finds its way out of the Arctic seas, although it may be many years before a given portion drifts away. Every summer, therefore, there is a steady stream of sea ice down the coasts of Spitzbergen, eastern Greenland, Baffin Land, and elsewhere in the south-flowing cold currents. This ice is not in a solid mass, but is broken in pieces or *floes*, and it is commonly called *floe ice*. The eastern coast of Greenland is so constantly bordered by a stream of this ice that it is exceedingly difficult for a boat to reach that coast. A similar, though less continuous, procession of floe ice moves southward in the Labrador Current past Baffin Land and Labrador. For a thousand miles the boat upon which the author went northward to Greenland in 1896 was in this floe ice (Fig. 404). In the warmer southern climate the ice rapidly melts, becomes weakened so that it breaks up, and finally disappears.

The Ice Foot. — Both in the Arctic and Antarctic there is, in the higher latitudes, a fringe of ice along the land, which has become known as the *ice foot*. It is of somewhat complex origin, being partly sea ice, partly snow that has slid or been blown upon it from the land, and partly the frozen spray of the waves that break upon the coast before the open sea is frozen. In some places rock fragments from the land are also incorporated in the ice foot. If the summer conditions do not suffice to remove this snow and ice accumulation, it may develop considerable thickness and width.

Icebergs. — Both the sea ice and the ice foot include a proportion of salt, though in both cases snow forms a part of the accumulation. Icebergs, on the other hand, are free from salt, since they are made of ice that developed on the land, and flowed down to the sea as a part of glaciers. These ice masses are often so abundant near great glaciers that they seriously interfere with the passage of boats; and

FIG. 404. — Floe ice in the Labrador Current off Baffin Land.

they often attain great size. In the Greenland waters some of the icebergs rise from 100 to 200 feet out of the water, and, as already stated, since only one-sixth or one-seventh of their mass is out of the water, their total height may be 1400 or 1500 feet. Such great ice masses float a long time before being melted, and some of those from Greenland float as far south as the Banks of Newfoundland, and even farther, where they are a menace to navigation (Fig. 405).

These Greenland icebergs are so large that collision with one often results in shipwreck, as when the *Titanic* was wrecked off the coast of Newfoundland on Apr. 14, 1912, and 1517 persons lost their lives.

By his invention of the *microthermometer*, a self-recording electrical resistance thermometer which measures temperature changes of a tenth of a degree, Barnes has been able to show definitely that the temperature rises as icebergs are approached. This has been tried out in detailed experiments in the Straits of Belle Isle, in a voyage from the St. Lawrence to Hudson Bay, and in several trips across the Atlantic Ocean. Icebergs 8 to 12 miles from the ship affect the microthermometer notably, and within a quarter mile of the berg the rise of temperature is very sharp indeed.

While icebergs float farther south than 45° in the western Atlantic, they are not found south of latitude 70° in the eastern Atlantic, because (1) there is no such extensive supply in that part of the Arctic,

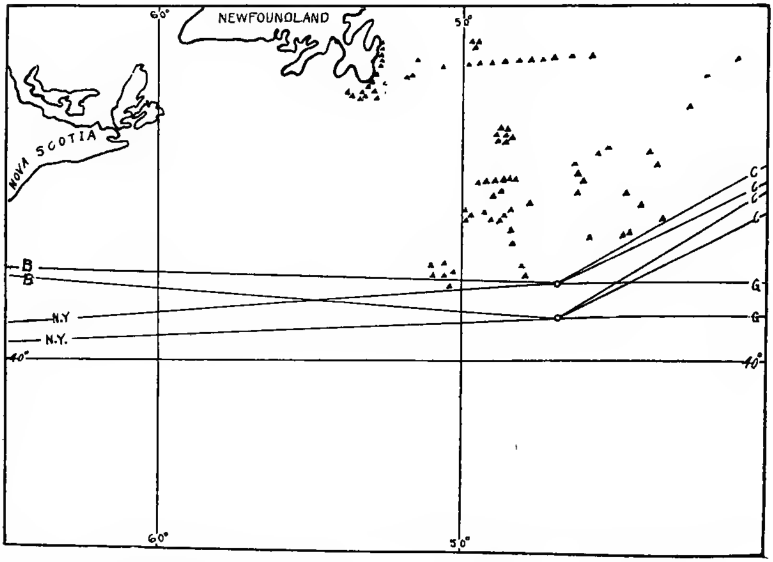


FIG. 405. — Distribution of icebergs (triangles) during the first half of April, 1909, showing how steamer routes between America and Europe are deflected southward. (Pilot Chart, U. S. Hydrographic Office.)

and (2) a warm current flows into these northern waters instead of a cold outflowing current, such as exists in the west.

Icebergs are found in front of the Alaskan glaciers which terminate as tidal glaciers in the fiords, and also in the Antarctic. In the latter locality the icebergs attain a diameter of several miles, forming great tabular bergs, like floating islands. The Antarctic icebergs and floe ice were well described by Wilkes, 1838–1842. These icebergs drift northward to latitude 40° or 50°.

Influence of Floating Ice. — Both icebergs and sea ice from near the coast transport much sediment, which falls to the sea bottom as the ice melts, icebergs being especially important in this respect. Both also affect the salinity of the water in which they melt. Again, this is especially true of iceberg and ice foot ice from which much fresh water is liberated; but even the floe ice aids in freshening the water, since snow that has fallen upon the Arctic ice is incorporated in it. Where icebergs are particularly abundant, they cause very notable freshening of the sea water.

All forms of floating ice are important in influencing the temperature of the waters in which they are melting. They chill the surface water, and this affects not merely the surface layers, but, by the sinking of the denser water, the influence is extended vertically even to the sea bottom. Doubtless a part of the cold of the sea bottom is due to this influence of melting ice in Arctic and Antarctic regions. The chill of the water is communicated to the air, and in the movements of the air it is borne to other regions. The chilly climate of the Labrador and Baffin Land coasts is partly due to this influence of sea ice, transmitted to the land by the onshore winds; and the chill of the melting ice is borne even farther south in the Labrador Current and carried by the winds to Newfoundland, Nova Scotia, and northern New England.

References to Literature and Maps

A. Agassiz. Three Cruises of the *Blake*, 2 vols., Boston, 1888, 314, 220 pp.; many papers in Bull. Mus. Comp. Zoöl.

R. Amengual. Lijeros Apuntes Sobre Oceanografía, Valparaiso, 1908, 413 pp.

H. T. Barnes. Ice Formation, with Special Reference to Anchor-ice and Frezil, New York, 1907, 260 pp.; Icebergs and their Location in Navigation, Smithsonian Report, Publication 2225, Washington, 1913, pp. 717–740.

J. Barrell. Relative Geological Importance of Continental, Littoral and Marine Sedimentation, Journ. Geol., Vol. 14, 1906, pp. 316–356, 430–457, 524–568.

G. E. Belknap. Deep Sea Soundings in the North Pacific, U. S. Hydrographic Office, Washington.

H. Berghaus. Atlas der Hydrographie, Gotha, 1891.

A. Buchan. Oceanic Circulation, Challenger Reports, Summary of Scientific Results, Part 2, 1895, 38 pp.

J. Y. Buchanan. On the Specific Gravity of Samples of Ocean Water, Challenger Reports, Physics and Chemistry, Vol. 1, 1884, 46 pp.

Challenger Reports. Voyage of H. M. S. *Challenger*, 50 vols., especially vols. 1 to 4; Summary of Scientific Results, 2 vols., London, 1897.

Challenger Society. Science of the Sea, London, 1912, 452 pp.

R. Chalmers. Tides of the Bay of Fundy, Ann. Rept. Geol. Survey of Canada, Vol. 7, 1896, pp. 14 M–20 M.

T. C. Chamberlin. On a Possible Reversal of Deep Sea Circulation and its Influence on Geologic Climates, Journ. Geol., Vol. 14, 1906, pp. 363–373.

C. Chun. Aus den Tiefen des Weltmeeres, Jena, 1900, 539 pp.

L. W. Collet. Les Dépôts Marins, Paris, 1908.

V. Cornish. Waves of the Sea and other Water Waves, London, 1910, 374 pp.

F. W. and W. O. Crosby. The Sea Mills of Cephalonia, Cassier's Magazine, Vol. 11, 1896, pp. 388–397.
G. H. Darwin. The Tides, Boston, 1898, 378 pp.
W. M. Davis. Winds and Ocean Currents, Journ. School Geog., Vol. 2, 1898, pp. 16–20; Waves and Tides, *ibid.*, pp. 122–132.
F. de Montessus de Ballore. Séismes Sous-marins et Tsunamis, La Science Séismologique, Paris, 1907, pp. 182–225.
Deutschen Seewarte. Atlas of the Indian Ocean, Hamburg, 1891; Pacific Ocean, 1896; Atlantic Ocean, 1902.
H. N. Dickson. Circulation of the Surface Waters of the North Atlantic Ocean, Phil. Trans. Roy. Soc., Vol. 196, 1901, pp. 61–203.
W. Dittmar. Researches into the Composition of Ocean Water, Challenger Reports, Physics and Chemistry, Vol. 1, 1884, 247 pp.
C. K. Edmunds. A Visit to the Hangchow Bore, Pop. Sci. Monthly, Vol. 72, 1908, pp. 97–115, 224–243.
H. Filhol. La Vie au Fond des Mers, Paris, 1892.
J. W. Flint. A Contribution to the Oceanography of the Pacific, Bull. 55, U. S. Nat. Museum, Washington, 1905, 62 pp.
J. S. Gardiner. The Indian Ocean, Geog. Journ., Vol. 28, 1906, pp. 313–332, 454–471.
J. W. Gregory. The Level of the Sea, Scottish Geog. Mag., Vol. 25, 1909, pp. 311–324.
E. Haeckel. Plankton-Studien, Jena, 1890.
R. A. Harris. The Tides: Their Causes and Representation, Pop. Sci. Monthly, Vol. 74, 1909, pp. 521–539; Manual of Tides, Part IV B, — Cotidal Lines of the World, Appendix 5, U. S. Coast and Geodetic Survey, Rept. for 1904, pp. 313–400; Part V, Appendix 6, Rept. for 1907, pp. 231–545; Cotidal Lines for the World, Nat. Geog. Mag., Vol. 17, 1906, pp. 303–309.
B. Helland-Hansen and F. Nansen. The Norwegian Sea, Report on Norwegian Fishery and Marine Investigations, Vol. 2, Bergen, 1909.
J. Hjort. The *Michael Sars* North Atlantic Deep Sea Expedition, 1910, Geog. Journ., Vol. 37, 1911, pp. 349–377, 500–523.
W. H. Hobbs. Origin of Ocean Basins in the Light of the New Seismology, Bull. Geol. Soc. Amer., Vol. 18, 1907, pp. 233–250.
L. Hugues. Oceanografia, Turin, 1904.
J. Johnstone. The Conditions of Life in the Sea, Cambridge, 1908; Life in the Sea, Cambridge, 1911.
L. Joubin. La Vie dans les Océans, Paris, 1912, 334 pp.
A. Kirchhoff. The Sea in the Life of the Nations, Man and the Earth, London, 1907, pp. 25–48.
W. Köppen. Der Ozean, Leipzig, 1902.
O. Krümmel. Handbuch der Ozeanographie, 2 vols., Stuttgart, 1907, 1911.
A. de Lapparent. Les Oceans, Leçons de Géographie Physique, Paris, 1898, pp. 683–700.
W. Libbey. Relation of the Gulf Stream to the Labrador Current, 6th International Geographical Congress, London, 1895, pp. 461–474.
W. Marshall. Die Tiefsee und ihr Leben, Leipzig, 1888.
E. de Martonne. Les Océans, Mouvements der Océans, Les Mers, — Traité de Géographie Physique, Paris, 1909, pp. 259–317.
M. F. Maury. Physical Geography of the Sea, New York, 1855, 474 pages.
G. W. Melville and H. G. Bryant. Some Results from the Drift Cask Experiment, Bull. Geog. Soc. Philadelphia, Vol. 4, 1906, pp. 49–56.
Prince of Monaco. Carte Générale Bathymétrique des Océans, 1 : 10,000,000, 8 sheets, Institut Océanographique, Paris, 1905; *ibid.*, revised to 1912–1913.
W. Moseley. Notes by a Naturalist, London, 1892.

J. Murray. Annual Range of Temperature in the Surface Waters of the Ocean, Geog. Journ., Vol. 12, 1898, pp. 113–134; Temperature of the Floor of the Ocean, *ibid.*, Vol. 14, 1899, pp. 34–51; Oceanography, *ibid.*, pp. 426–439; The Oceans, Mills' International Geography, New York, 1899, pp. 60–71; The Deep Sea, Scottish Geog. Mag., Vol. 26, 1910, pp. 617–624; Exploring the Ocean's Floor, Harper's Magazine, Vol. 122, 1911, pp. 541–550; The Ocean, New York, 1912, 256 pp.

J. Murray and J. Hjort. The Depths of the Ocean, London, 1912, 821 pp.

J. Murray and A. F. Renard. Deep Sea Deposits, Challenger Reports, London, 1891, 525 pp.

F. Nansen. Bathymetrical Features of the North Polar Seas, Christiania, 1904, 232 pp.

P. Pelseneer. L'Exploration des Mers Profondes, Paris, 1892.

A. Penck. Das Meer, Morphologie der Erdoberfläche, Stuttgart, 1894, Vol. 2, pp. 460–662.

O. Pettersson. On the Influence of Ice-Melting upon Oceanic Circulation, Geog. Journ., Vol. 30, 1907, pp. 273–303.

J. E. Pillsbury. The Gulf Stream, U. S. Coast and Geodetic Survey, Appendix 10, Rept. for 1890, Washington, 1891, pp. 461–620; *ibid.*, Nat. Geog. Mag., Vol. 23, 1912, pp. 767–778.

R. Quinton. L'Eau de Mer, Paris, 1904.

J. Richard. L'Oceanographie, Paris, 1907, 398 pp.

R. D. Salisbury. The Mineral Matter of the Sea, Scottish Geog. Mag., Vol. 21, 1905, pp. 132–136; *ibid.*, Journ. Geol., Vol. 13, 1905, pp. 469–484.

G. Schott. Physische Meereskunde, Leipzig, 1910, 143 pp.; Geographie des Atlantischen Ozeans, Hamburg, 1912.

N. S. Shaler. The Depths of the Sea, Sea and Land, New York, 1894, pp. 75–152; The Resources of the Sea, Man and the Earth, New York, 1905, pp. 139–149.

C. D. Sigsbee. Deep Sea Sounding and Dredging, U. S. Coast and Geodetic Survey, Washington, 1880, 221 pp.

J. W. Spencer. The Submarine Great Cañon of the Hudson River, Geog. Journ., Vol. 25, 1905, pp. 180–190.

A. Steuer. Leitfaden der Planktonkunde, Leipzig, 1911.

Z. L. Tanner. Deep Sea Exploration, U. S. Fish Commission, Washington, 1892.

R. S. Tarr. The Arctic Sea Ice as a Geological Agent, Amer. Journ. Sci., Vol. 153, 1897, pp. 223–229; The Fishing Industry of New England, Bull. Amer. Bureau of Geog., Vol. 2, 1901, pp. 1–16.

Wyville Thomson. Depths of the Sea, London, 1874, 527 pp.; Voyage of the *Challenger:* The Atlantic, 2 vols., New York, 1878, 391, 340 pp.

J. Thoulet. Océanographie, 2 vols., Paris, 1890, 1896; L'Océan, les Lois et ses Problèmes, Paris, 1904, 397 pp.; Résultats les Campagnes Scientifiques du Prince de Monaco, 1902, 76 pp.

U. S. Census. Fisheries of the United States, Fisheries of Alaska, Washington, 1911, 324 pp.

F. Viezzoli. L'Adriatico, Parma, 1901, 207 pp.

J. Walther. Allgemeine Meereskunde, Leipzig, 1893, 296 pp.; Boston, 1899, 180 pp.

J. J. Wild. Thalassa, London, 1877.

C. Wilkes. Antarctic Cruise, Vol. 2, U. S. Exploring Expedition, 1838–1842, Philadelphia, 1844, pp. 297–387; Hydrography, *ibid.*, Vol. 23, 1861, 514 pp.

R. S. Woodward. On the Form and Position of the Sea Level, Bull. 48, U. S. Geol. Survey, 1888, 88 pp.

For references to other valuable oceanographic data, see the summary by Murray in "Depths of the Ocean," pp. 1–21.

PERIODICALS

Memoirs and *Bulletins*, *Museum of Comparative Zoölogy*, Cambridge, Mass.
Charts, *Tide Tables*, and *Annual Reports*, *U. S. Coast and Geodetic Survey*. Washington, D.C.
Pilot Charts, *U. S. Hydrographic Office*, Washington, D.C.
Bulletins and *Commissioner's Reports*, *U. S. Bureau of Fisheries*, Washington, D.C.
Charts, *British Admiralty Office*, and similar bureaus of other European countries.
Pilot Charts, *British Meteorological Office*.
Bulletin de Musée Océanographique de Monaco.
Publications, *Institut für Meereskunde*, Berlin.
Annalen de Hydrographie, Berlin.

CHAPTER XX

LIFE IN THE OCEAN

Distribution of Ocean Life

Conditions Governing Distribution. — The distribution of life in the ocean is brought about partly by the voluntary movements of the organisms, partly by the water currents. Even organisms that are fixed are commonly subject to the latter influence in their larval stages. Since the ocean water is ever in motion, there is, therefore, provision for wide distribution. The extent to which this distribution is carried on, depends upon a variety of conditions, some of which are stated in the two following paragraphs.

(1) *The Kind of Organism.* — Some are fixed and require a special kind of habitat, as muddy bottom, or sand, or rock, or surf-beaten coast. Others float about with such limited provision for locomotion that they are practically at the mercy of the currents. Still others are free-swimming and are capable of moving at will.

(2) *The Physical Conditions.* — Among the physical conditions which influence distribution of marine organisms are temperature, sunlight, oxygen supply, food supply, and depth. Those that live on or near the coast are also influenced by salinity, by the clearness of the water, by floating ice, and by the nature of the coast.

Variety of Organisms. — The organisms include both plants and animals, the former being necessarily limited to those upper portions of the ocean in which there is sufficient sunlight for plant growth, while the latter range from the surface to the bottom of the sea. They vary also in size from microscopic forms to the huge whale, the largest member of the animal kingdom, and to forms of seaweed, or kelp, in the vegetable kingdom which grow to a length of several hundred feet, rivalling the height of the highest trees, though having less diameter, a few inches only, and much less bulk. The largest plants grow on the land. In the ocean only a very few species of higher plants, such as abound on the land, are to be found, and these are living in protected waters along the coast. In the open ocean the plant life is all of lower orders. Among marine animals, too, the greatest abundance is found in the lower orders of invertebrates, and next most abundant are the fishes, the lowest of the great divisions of the vertebrates. All the higher divisions of the vertebrates are represented among marine animals, the mammals by the whale, seal, walrus, manatee, and others, the reptiles by the turtles and other forms, the birds by large numbers of species which look to the sea for their food and spend a greater or less proportion of their time in the ocean. There are no birds that live habitually in the sea, though many spend most of their time in it and the remainder on its margin. Some even have lost the power of flight, like the auk and the penguin. The birds, reptiles, and mammals obtain their oxygen supply from the air, rising to the surface for it; but the fishes, invertebrates, and plants obtain it direct from the water.

Relations of Plants to Animals. — As upon the land, the plants of the sea are able to transform mineral substances from the surrounding medium into organic tissue. In this process sunlight is necessary, and plant life in the ocean is, therefore, confined to the upper layers into which sunlight penetrates. The animals of the sea, as upon the land, need plant life as a basal food supply, since animal life has not the power of transforming mineral substances directly into organic tissue. Since the surface organisms, both plant and animal, sink upon their death, the range of animal life is extended even to the ocean bottom, for sunlight is not a necessary part of their life processes, if food is supplied to them which has been prepared in the zone of sunlight.

Contrast with Land and Air. — There is here a very wide difference between conditions in the ocean and on the land. The base of the atmosphere, where it rests upon the land, is a zone of abundant organic life, and this zone is extended into the earth a few inches or feet, rapidly grading into a zone where organisms are completely absent. The life zone is also extended a short distance into the air, again grading into a barren zone. In the ocean, on the other hand, while the surface zone of sunlight is the most densely occupied portion, organisms are found in abundance both on the dark sea floor and at intermediate depths.

Adaptation to Environment. — In the ocean, as on the land, there is an adaptation to environment, with the development of much variety of form, colour and habits. A large proportion of these peculiarities are evidently related to securing food, or to escaping enemies. There is the usual great struggle for existence, some forms feeding upon others, some rivals for the same food. In the clear, open waters of the ocean, the chance of escape from destruction by enemies is far less than on the land or even on the coast, where various means of hiding are possible. Speed of movement and transparency are common means of protection, but the inefficiency of the latter is clearly indicated by the fact that many fishes produce scores of thousands of eggs in order that one may escape the chances of destruction and arrive at maturity.

Cause of Wide Distribution. — There is wider distribution of organisms in the ocean than on the land (1) because there are less differences in temperature, (2) because the medium in which they live is in motion, (3) because, excepting along the coast, there are fewer variations in environment.

Difference in Bodily Structure. — Also, because of the medium in which they live, there is a difference in the bodily structure of the marine and land animals, a very large proportion of the former being of about the same weight as the water which they displace, or a little heavier. On the land the greater number of plants are fixed in place; but in the sea, the plants are mainly floating forms, though this is not true along the coast line and in shallow water, where the condition is much like that of the land.

Animals of the land, on the other hand, are freely moving in the main; but while this is also true of a large proportion of the marine animals, there is, in the sea, a much greater number of fixed forms along the coast and on the sea bottom than among land animals. Among these fixed forms are many species which protect themselves against enemies or against the waves and currents by a mineral cover, usually carbonate of lime, as is illustrated by the corals and by many shells. It is out of the remains of these organisms that many of the limestone beds of the lithosphere were made in ancient seas.

Abundance of Life

The Larger Animals and Plants. — The vast abundance of organic life in the ocean, especially in the upper layers and along the coast, has long been known. Many coast lines are bordered with luxuriant seaweed growth, encrusted with barnacles, or fringed by coral reefs, mangrove swamps, or salt marshes. There are tracts of floating seaweed or sargassum; there are great schools of fishes; and there is the huge whale, narwhal, seal, and walrus, as well as vast numbers of birds which feed upon marine organisms. It has also been known that the surface water teems with minute organisms which may be strained out by means of tow nets in which, after a short interval of towing, as many as 50 different species and thousands of individuals are found. Every pail of water dipped from the ocean surface is a small world of microscopic and sub-microscopic life.

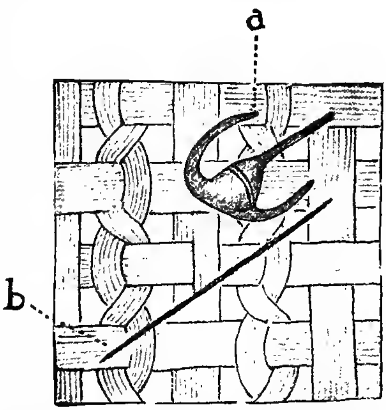


FIG. 406. — Small plants of the deep sea. at *a* and *b*, caught in silk cloth netting. The highly magnified square above is about $\frac{1}{4}$ of a square millimetre, or about $\frac{1}{100}$ of an inch on each side. (Murray.)

Invisible Inhabitants of the Sea. — Only very recently, however, has it been proved that even this is but a part of the life of the ocean. There are forms so small that they sift through the finest meshes of the silk tow net (Fig. 406). This difficulty is met by an ingenious machine, the *centrifuge*, which rapidly rotates a sample of water so that even the most minute forms are thrown together by centrifugal force, the living contents of about 300 cubic centimetres of water being concentrated in a single drop of water, where they are counted under the microscope. In this way it has been found that the surface water down to a depth of from 30 to 160 feet is densely populated by minute plant cells. The minute organisms of the surface layers of the ocean are known as *plankton*.

Upon the abundance of such life, Murray writes as follows: "We now know that the whole of the surface waters of the ocean are crowded with minute unicellular algæ, which are ever busy, under the influence of sunlight and chlorophyll, converting the inorganic substances in sea water into organic compounds, which in turn supply not only the food of the vast majority of marine animals which live in surface and intermediate waters, but also of the myriads of creatures living near and on the sea floor, miles beneath the level to which the sun's rays can penetrate. The surface waters may be regarded as vast floating meadows, each great region having its own species and a soil (as it were) and other conditions which make for abundance or scarcity. The vegetable matter, in the form of phytoplankton, present in the surface waters of the ocean down to a depth of 200 fathoms, is probably much more abundant than that in the layer of vegetation which covers the land surfaces of the globe. The bodies of these minute unicellular algæ, which often have calcareous, siliceous, or chitinous shells, fall to the bottom after death, together with the dead bodies of the animals which browse in these meadows; accumulating on the surface of the deep sea oozes and clays, they supply nourishment for the creatures that crawl over the bottom of the sea."

The Four Oceanic Zones

There are four great zones in the ocean, with conditions sufficiently different to give rise to faunas of notably different characteristics. There are (1) the littoral zone, or the coast and shallow waters near the coast, (2) the pelagic zone, or the upper layers of the ocean water, (3) the abysmal zone, or the deep sea, (4) the zone of intermediate depths. Each of these will be considered separately for the purpose of bringing out some of the noteworthy differences.

Life Along the Coast (Littoral)

Resemblances to Life on Land and in Air. — The coast line presents conditions intermediate between those of the land and sea; and accordingly there are resemblances between the life in the two, while some of the species go freely from one to the other. The polar bear, for instance, is probably to be classed as a land animal, though it spends a large share of its time on the ice floating in the sea; the seal and walrus are doubtless to be classed as marine animals, though staying out of the water, on the shore or the floating ice, a large part of the time. Many birds live in the sea or in the air above the sea the greater part of the time, coming ashore mainly for feeding, as also do the marine turtles. Some of these forms wander far over the sea, as the fur seal does when it makes its journey between breeding seasons from the Pribilof Islands even as far as the southern Pacific; but the great majority are confined to the coast region and the shallow waters bordering it. This vertical range is limited, because they depend upon the atmosphere for their organic supply.

Variation with Nature of Coast. — On the very coast line there is normally abundant life, but the abundance and variety vary with the nature of the coast, as well as with temperature, food supply, and other conditions. The sandy coasts are relatively barren, for the sand is too shifting for fixed forms of life, and the variety of burrowing animals adapted to life in the shifting sands is not great. Some land plants which can withstand the occasional bath of salt spray live along the upper margin of the zone of wave action, and a limited number of a few species of burrowing animals live in the wave zone. Some of these, like certain species of crabs, make journeys to the land vegetation for their food. On the whole, and as contrasted with the littoral zone in general, the sand beaches may be considered oceanic deserts, as may also the zones of shifting sands in shallow water offshore. Even more of a desert is the boulder and pebble beach, in which the waves move the surface about with such force and frequency that life is practically prohibited.

Along the shores of protected bays, shifting sands are less extensive, and many portions of the coast are of clay or of fine-grained sand, not subject to frequent movement. Here land vegetation comes down to the sea, and some forms actually invade it with dense growth, as in the mangrove swamps, the salt marshes, and the eel grass patches. Such luxuriant plant growth supports an abundant and varied marine fauna, quite different in character from that on neighbouring, open-coast, sand beaches, but including a large number of burrowing animals, such as the clam and the scallop. In the shallow waters of the bays there is often an abundance of fixed forms, as, for instance, the oysters, which live in such numbers that they sometimes build layers of shells by the death and accumulation of the shells of successive generations.

On the rocky coasts, whether exposed to the ocean waves or in protected bays, the littoral life is mainly fixed, for there is a solid foundation on which to grow, and the waves would make short work of organisms that were not firmly fastened. Various forms of seaweed constitute the most noteworthy plant growth on such rocky coasts; and, among animals, the barnacle is conspicuous, — an animal which passes through a free-swimming larval stage, then, attaching itself to rock or other solid foundation, becomes encrusted in a calcareous armour. Numerous other species live in this zone, some fixed, some clinging to fixed forms, some holding on by means of suction and moving about slowly, some burrowing into the rock, and some swimming about when the water is quiet, or in the zone just beyond the breakers.

Other Causes for Variation. — There is much difference in form, habit, and abundance of marine organisms in the littoral zone, for there are varied conditions, even within short distances. In this respect there is resemblance to land life, rather than to other zones of ocean life where there is far greater uniformity of conditions. Besides local differences due to the variation in environment, there are differences due to climate; for example, the Arctic, temperate, and tropical littoral life present wide differences. This may be illustrated by contrasting the two extremes, the conditions in the temperate zone being intermediate.

Littoral Life in the Arctic. — In the Arctic the littoral fauna and flora are greatly restricted by the temperature, which is unfavourable to an abundant and varied life. To this is added the effect of ice, which transforms exposed coasts to marine deserts within the zone of ice attack. In the shallow waters offshore, where ice does not reach, there is abundant and varied life, and in the cold northern waters are many large animals which feed upon this life — diving birds, seals, walrus, and large fishes, such as cod and halibut. Shallow banks in the cold north temperature waters and along the outer margin of the Arctic zone are our leading sources of food fish.

Littoral Life in the Tropics. — In the tropical zone the littoral fauna, in places favourably situated for food supply, is wonderfully varied and abundant. As upon the land, this abundance and variety can be ascribed in part to the warmth and the bright sunshine, which encourages plant growth. Probably no part of the ocean is so densely occupied by organisms as the shallow coastal waters of the tropical zone, as especially exemplified by the coral reef life. Here the bottom is studded with fixed forms in great variety and occupying almost every square inch of the surface, while among the fixed organisms are burrowing, crawling, swimming, and floating species. As contrasted to the Arctic life, the marine organisms of the torrid zone are beautiful in form and colour.

Gradation toward the Deep Sea. — From the coast out toward the deep sea there is a gradation toward the abysmal fauna, and it is difficult to tell where to draw the line. It may, perhaps, be drawn in those depths where the penetration of sunlight ceases to be effective in encouraging plant growth, say 200 or 300 feet. Beyond it there is little plant life, and it is beyond the reach of animals of land origin, and the fauna is purely marine in all its characteristics. Some of the littoral species extend out into this deeper zone, but in the main the fauna is different.

Favourableness of Littoral Zone. — The great variety of life in the littoral zone is due to the variations in the environment, — the variations in temperature, exposure, nature of coast, salinity, oxygen supply, and food supply. Several of these factors also influence the abundance of life, but none more effectively than oxygen and food supply. In these respects the littoral zone is, in general, favourable to abundant life, for the water is aërated in the surf zone, and both oxygen and food supply are brought to the animals by the waves and currents. Along the coasts, currents are more active than elsewhere in the ocean, for local differences in temperature, in salinity, and in wind are causing constant water movement, and the tidal currents are more effective along the coast than elsewhere in the ocean.

Life at the Surface (Pelagic)

Wide Distribution of Minute Organisms. — Mention has already been made of the great abundance of minute organisms in the surface layers of the ocean. These extend from shore to shore of all the oceans, and throughout all zones, being apparently somewhat more abundant in the colder waters, with abundant oxygen, than in the warmer waters. These minute organisms include both plants and animals, and they are to be classed as floating forms, for, though provided with some power of locomotion, they are essentially at the mercy of waves and currents. Accordingly the species have an extraordinarily wide distribution.

Larger Pelagic Forms. — Besides these minute forms are many larger floating and swimming species, and some clinging and fixed forms attached to floating bodies such as logs and seaweeds, or to swimming animals. In the Sargasso Sea, for example, there is a miniature world of plant life and dependent swimming, crawling, and fixed forms of animal life. Among the larger animals are numerous fishes, some like the herring and mackerel, swimming in great schools, others moving singly like the shark and swordfish. The whale also roams in the surface and upper layers of the ocean. A multitude of floating species of jellyfish and other forms of animal life also inhabit this zone, and great numbers of the young of larger animals, especially in the coastal waters where many of the fixed forms have a free-swimming larval stage.

The Food of Pelagic Animals. — The basis for the existence of the pelagic animal life is the abundant plant life, notably the microscopic algæ already mentioned. They measure from 0.01 to 0.03 of a millimetre and are so small that from 3000 to 12,000 live in each litre of water in the upper layers. The abundance of plankton is less in the open Atlantic than in the coastal seas, and less at the very surface than at a short depth below the surface, being most abundant in depths of from 40 to 200 feet. Many of these plants, such as the diatoms, have silicious tests, others, *Coccolithophoridæ*, calcareous (Fig. 407). Upon the minute plant and animal life of the surface even huge whales depend for their food, straining out the organisms from the water as a tow net does.

Colour of Organisms. — While there are coloured forms of animal life in surface layers of the ocean, and even some that are black, the great majority are either transparent, translucent, or blue in colour. This serves as a protection, rendering them invisible even when viewed from below.

FIG. 407. — A small calcareous plant from the sea, one of the *Coccolithophoridæ*. In volume these make up the main part of the plankton. Their diameters may be only $\frac{1}{250}$ to $\frac{3}{250}$ of an inch, so that they go through the finest nets and are taken only with the centrifuge. Such plants are found in the stomachs of all pelagic animals and make up a large part of the deep sea oozes. (Murray.)

Reason for Wide Distribution. — Although there are many different species in the pelagic fauna, one of the most notable facts concerning them is their wide distribution. Equally noteworthy is the absence of local variations in the fauna and flora in a horizontal direction, for there are not ordinarily sufficient differences to lead to local development of special fauna and flora. The chief differences are related to currents, cold and warm, and to variations in the conditions of the water, especially in the neighbourhood of the coasts. Vertically, however, there are very striking differences, for there is change in temperature, sunlight, and amount of oxygen in a very small vertical range. Even the lowly algæ are found to differ in species with depth.

Predominance of Floating and Free-swimming Forms. — The pelagic forms are mainly floating or free-swimming, and it is important, therefore, that they, especially the former, shall have about the same weight as the water which they displace. Many species actually float, as the sargassum does, by means of air-filled cells; and the Portuguese man-of-war by means of an air-filled sac; others keep afloat by slight movement or by swimming; others still can rise and sink at will by means of chambers into and out of which water can be forced.

Lack of Protection from Enemies. — In general the organisms live a life of chance, with little or no provision for defence, though some are protected by shells, or can swim rapidly, or can discharge cells which benumb enemies, as the Portuguese man-of-war does, causing a feeling like an electric charge. The smaller are, however, practically at the mercy of the larger, and escape from destruction is reduced mainly to a mere matter of chance. Only by reason of the wide distribution, and abundant provision for succession, as in the great number of eggs, the fission of cells, etc., is it possible for the forms to exist in such abundance. The chance of survival must be but one in many thousands, if one may judge from the extensive provision made for succession by some of the animals which pass through a free-swimming larval period.

Life in Intermediate Depths

It has been the prevailing belief that while the ocean surface is densely populated, and the ocean bottom is also occupied by life in considerable variety and abundance, there is an intermediate zone, thousands of feet in depth, in which there was a practical, and perhaps complete, absence of life. Yet it has seemed strange that among the animals brought up in the dredge from the deep sea there are some that are coloured, others black, some blind, others with highly developed eyes. Even related species presented wide differences

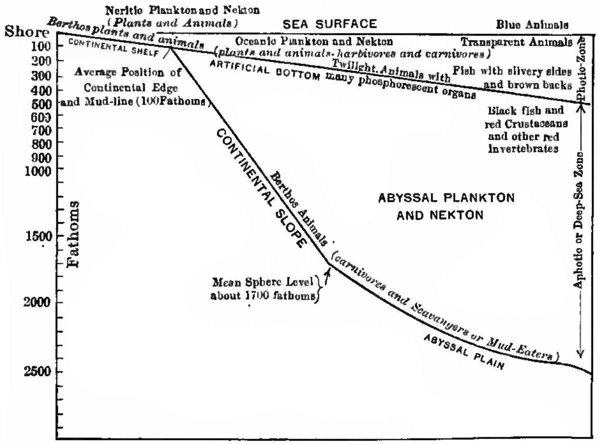


Fig. 408. — Diagram to show the areas occupied by various types of oceanic plants and animals. (Murray.)

which were difficult to explain on the assumption that they lived side by side in the darkness and uniform temperature of the ocean bottom.

The expedition of the *Michael Sars* has evidently solved this problem in the discovery that the intermediate zone is inhabited. This has been proved by towing nets at different depths and also by using a tow net that can be automatically closed at any depth. Thus animals were secured in the intermediate layers that had previously been thought to belong to the bottom fauna because they were captured in the dredge on its way up through the intermediate layers. Not enough knowledge is as yet at hand to make possible a very complete statement of the life conditions in this intermediate zone. There is certainly a decrease in abundance of life from the sunlit surface layers, through the twilight zone, to the zone of darkness; and it is possible that there is a lower zone in which there is no life.

It is quite possible that in some of the deep sea fishes the telescopic eyes, having a cylindrical shape, with a convex lens at the end, may be useful in the zone of twilight; and that the red and black colours which prevail in the deep sea are of protective value. In hauls between 600 and 1500 feet, the nets bring up large quantities of deep red shrimp and black fishes. These twilight animals, which include fishes, worms, cuttlefishes, and crustaceans, may be assumed to be invisible from above (Fig. 408).

Little is known about the distribution and variation of these animals of the intermediate zone. One would expect them to be widely distributed because of the uniformity of conditions amid which they live; and it would seem probable that variation would be more rapid and important vertically than horizontally. Their food supply must come from the zone of sunlight; but whether they obtain it as it falls toward the bottom, or whether the animals of one layer prey upon those of the layer above and these in turn upon the next layer, thus transmitting the sunlight influence into the zones of twilight and darkness, cannot now be told. It is a great and interesting field for exploration, only a mere beginning having been made.

Life on the Ocean Bottom (Abysmal)

Relation to Temperature, Oxygen, and Food Supply. — By far the greater part of the ocean floor is inhabited, and perhaps it all is. The abundance of life varies with the temperature and the supply of oxygen and food. Thus where warm ocean currents sweep against the bottom, insuring warmth and both oxygen and food, animal life is varied and abundant. Such a condition exists southeast of New England, where the Gulf Stream flows along the border of the continental shelf. There is also abundant life on the Newfoundland Fishing Banks over which the cold Labrador Current sweeps.

In greater depths life decreases in abundance and variety, but it is possibly absent from some of the greater ocean depths and in some of the colder waters. The great cold, sometimes as low as 30° or 31°, necessarily reduces vitality, and the slow supply of oxygen places a distinct limitation on life. There seems usually to be oxygen present, however, in sufficient quantities for the existence of life, which is interpreted as indicating the existence of a slow circulation of cold surface waters along the ocean bottom. Where barriers exist to check free circulation, there is a diminution of oxygen, and it is probable that there are areas in which there is so little oxygen that life cannot exist. Such is known to be the case in the Black Sea, where the bottom water is so charged with sulphuretted hydrogen that with the exception of bacteria no life exists.

The Monotony of Abysmal Conditions. — The deep sea animals exist in the midst of the most monotonous uniformity of conditions, — amid uniformly low temperatures, in a nearly motionless medium, in absolute darkness, excepting for phosphorescent light, on a surface that is prevailingly a vast plain of ooze and red clay. Temperature differences are the main cause for variation, and these are found mainly in a vertical section, along which there is but slight variation in the deeper waters of the open ocean. Though it was once thought that the great pressures were a dominant factor, and that animals could not exist with such pressures, amounting to nearly 5 tons per square inch in a depth of 25,000 feet, it is now known that the pressure is of no importance; for once the animal is adjusted to them there is pressure equally in all directions both within and without the body, and the animals are as unaffected by them as we are by the 15 pounds which is pressing on every square inch of our bodies. Only when they are raised to regions of lesser pressure, and the expansion from within is exerted on the bodies, is this enormous pressure effective. Then the skin may be actually cracked open by the internal pressure.

Absence of Plant Life. — Since no plant life exists in the zone of darkness of the ocean, the animals of the sea floor are wholly dependent upon the supply that rains down upon them from the densely inhabited upper layers. This is devoured as it falls, and the ocean bottom ooze supplies food to burrowing animals, while doubtless also one form of ocean bottom life preys upon another, as elsewhere in the world. Life on the ocean bottom is necessarily limited by this food supply, but it is sufficient to support a varied and abundant life where other conditions are favourable.

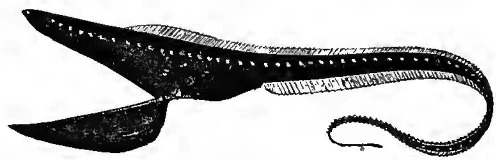


Fig. 409. — A fish from the deep sea with transparent fins. (U. S. Fish Commission.)

Adaptations to Abysmal Environment. — Among the ocean bottom animals are free-swimming animals, including fishes, some wholly blind, some with eyes whose use can be explained only on the assumption of the existence of phosphorescent light, which, indeed, it is known that some of the fishes carry about with them. There is one, for instance, that has a tentacle-like projection from its head, the end of which emits a phosphorescent glow. It has been called a *deep sea lantern*. Many forms burrow in the ocean bottom ooze, passing it through their digestive tracts as earthworms do the soil. Others crawl over the ocean bottom, and still others are fixed in place; but on a wide expanse of ooze-covered plain there is not an abundance of solid pieces upon which these deep sea animals can fix themselves. Thus, with the scarcity of suitable foundation, shells are found encumbered with clinging species, cables are quickly encrusted, and even bottles, thrown over from ships, have been dredged up with a cover of fixed forms of ocean bottom life. Some forms of animal life have developed special means for fixing themselves in the ocean bottom ooze, such, for instance, as enclosing some of the ooze in a bag-like growth at the base which serves as an anchor, or the growth of root-like branches which spread out through the ooze. These means of fixing the animals in place could be successful only in water with little or no motion — otherwise the fine-grained ooze would be washed away.

Survival of Animals of Past Ages. — That the uniformity of conditions of the ocean floor should be favourable to the survival of animal types of bygone ages, elsewhere destroyed by species better fitted to the environment, seems natural. It was, therefore, not a matter of great surprise when stalked *crinoids* (Fig. 410) were found living in the deep sea, though long since exterminated in the shallow waters where they were once so dominant as to actually form the bulk of certain layers of limestone rock. There may be other instances as yet undiscovered, for much of the ocean depths is yet to be explored.

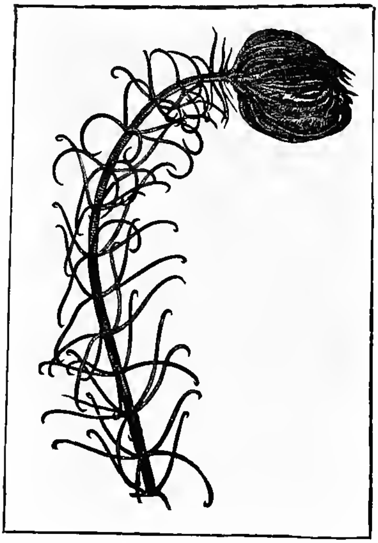


Fig. 410. — The stalked crinoid or sea lily, a deep sea animal. (Alexander Agassiz.)

The Ocean as a Source of Food

The ocean is important to man in a number of ways — as a great highway of commerce, as a barrier to distribution of life, as a source of vapour for the atmosphere, as a modifier of climate, and in other ways. It is also an important source of food supply. Some communities obtain a very large part of their food from the sea, as, for instance, in Norway and in Newfoundland; and they then have a surplus for distribution among other communities.

In the fisheries it is the coast line and the shallow waters and banks of the continental shelf that are the chief sources. Among the forms obtained are burrowing animals, like the clam, fixed animals like the oyster, crawling kinds like the lobster, and free-swimming kinds like the fishes. All of the great groups of the animal kingdom contribute to the food supply from the sea, the invertebrates, fishes, reptiles, birds, and mammals; but by far the most important are the true fishes. Some of these are surface forms, like the mackerel and herring; but a large number live on or near the shallow bottom, like the halibut, codfish, haddock, plaice, etc. Still others are fish that, though living in the sea the greater part of their lives, ascend into fresh water to lay their eggs, or spawn. Of these the salmon and shad are by far the most important. The open ocean, far from land, is not an important source of food fish, and the deep sea bottom and intermediate layers are not drawn upon at all.

Besides food, the marine animals furnish a great number of other useful products, — whale and seal oil, whalebone, sealskins, walrus ivory, coral, sponges, tortoise shell, pearls, etc. The annual value of the fisheries of all kinds in the United States is equal to $61,000,000. This, however, is only about equal to some of the minor crops on the land, such as sugar beets. The fishery products of Japan and Great Britain exceed those of the United States in value, the total for the world being nearly $440,000,000 per year.

For references to literature, see pp. 665–668.

CHAPTER XXI

MOVEMENTS OF THE OCEANIC WATER

Types of Movement

It is probable that all parts of the ocean water are at all times in motion. Some of these movements are slow and imperceptible, others are quite obvious. They are due to a complex series of causes often completely interrelated. Some of the movements are in the form of waves; others are currents, or drifts of water. Some of the currents are not related to the waves in origin, while others, such as the tidal currents, develop as a result of the wave, and still others, such as the wind drift current, are developed by the same cause that produces the wave.

These various and complex movements may perhaps best be understood if discussed under three somewhat arbitrary divisions: (1) waves, not including the tidal wave; (2) currents and drifts, not including the tidal currents; (3) tides.

Waves

This term is commonly understood to refer to wind waves, but there are other forms of wave developed in the ocean, such as the earthquake wave, the iceberg wave, the wave due to differences in atmospheric pressure, and the tidal wave. With the exception of the latter (p. 700), these various forms of wave will now be discussed.

Wind Waves

Currents accompanying Wind Waves. — When the wind blows over the water, there is friction at the surface of contact, as a result of which two quite distinct motions are caused: (1) a forward drift of the water in the direction of the wind, (2) the development of a wave translation. With continued friction both of these movements are increased until (*a*) a well-defined current is set up, and (*b*) waves of considerable height are formed. Thus, in the trade wind belt, or in other zones of regular winds, both currents of surface water and waves move in the direction of the prevailing wind, the current advancing much more slowly than the wave, and both lagging behind the wind which causes them.

Relation of Waves to Velocity of Wind. — The wind waves vary in height from tiny ripples to great billows, rolling "mountain high."

With a gentle breeze only small waves develop, reaching a height of but a foot or two, but if the wind increases to a gale, the ocean surface is quickly transformed to a series of great waves, and, if the wind continues and blows over a large expanse of ocean, the waves become of great size. These are formed by the powerful friction of the moving air, by the adding of wave upon wave as the gusts strike the water surface, and by the transmission of the impulse to the water below the surface. The wind waves sometimes attain a speed of 50 or 60 miles an hour, though commonly less, even down to 20 to 25 miles. The water itself does not move forward at this rate, but merely the translation of the wave form. One may illustrate this with a rope, when, by giving a quick shake at one end, a wave is caused to pass through the rope to the other end. As the wave form thus rapidly advances, another follows, with others behind, each wave consisting of a *crest* or higher part, grading down on both sides to a hollow, or *trough*, the crests and troughs being roughly parallel and linear.

FIG. 411. — Storm waves on the open ocean.

Height and Length of Waves. — The height to which waves rise in the open ocean has been greatly exaggerated. A wave 20 feet from trough to crest is very high, and it is probable that they rarely rise more than 40 or 50 feet. In the southern ocean, where the stormy west winds blow over a vast stretch of water, waves are said to be so high, and the distance between trough and crest so great, that sailing vessels are temporarily becalmed when sinking into the trough of the billows. It is said that exceptional waves 1500 feet long have been seen. The wave length, however, is not usually over 600 feet, and may be 300 feet or less in length. Indeed, most waves that reach the coast are under 25 feet in length.

While the wave form moves rapidly forward, an object floating on the surface is alternately raised and lowered, as crest and trough pass it, proving clearly that the water itself undergoes no such motion as the wave has. If it did, a vessel would be helplessly carried along. The water particles undergo a circular motion. In the trough they are moving backward (Fig. 412); as the crest approaches they rise, at

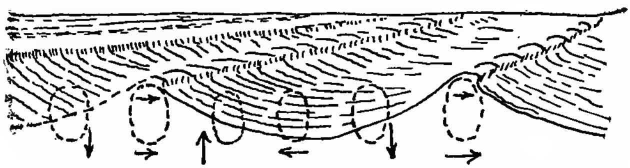


FIG. 412. — Movement of water particles in waves. (de Martonne.)

the crest they move forward, and on the rear of the crest they move downward.

The wave form is a surface feature, but the movement of the water extends far below the surface, though with diminishing force. It is certain that under large ocean waves there is a motion sufficiently powerful to move sand at a depth of from 400 to 600 feet, but even this makes the wave motion merely a superficial phenomenon of the deep ocean water.

Ground Swell. — The movement of the ocean, once started, will continue even far beyond the exciting cause, especially if there are large waves, advancing 25 to 50 miles an hour. It is as a result of this that great waves lose their irregularity and are long, deep swells. Such waves, called *ground swell*, or *rollers*, are often felt even on a glassy sea when there is no wind. Generated in some regions where there is wind, they travel scores or even hundreds of miles beyond their source before they die out. Thus the ocean surface is rarely absolutely calm and free from motion, since a ground swell may come from two or three distant sources in any direction at the same time.

Whitecaps and Wind-drift Currents. — The ground swell is a fairly smooth, regular wave form; but when the wind is blowing strongly, a wind wave is far less regular. During a heavy wind the waves consist of a series of billows whose intervening troughs have much irregularity of form. Their surfaces (Fig. 411) may have a series of small waves superimposed upon them, and their crests may be broken by the force of the wind, forming *whitecaps*, or great foaming crests, so steep on the side away from the wind that the crest often breaks and forces forward a wave of foaming water. The friction of the air sets up a current, or an actual movement of the surface water, quite independent of the wave itself. Therefore, a boat adrift in the sea, though rising and falling with the passage of each wave, will also be carried forward, both by the wind and by the *wind drift current* of surface water.

Whitecaps sometimes break against a ship and wash the decks from end to end. Normally a vessel rises and falls with the passage of the crests and troughs, but such *combers* may temporarily quite submerge the boat. To small boats they are exceedingly dangerous. During heavy gales the wind actually blows the water from the wave crests in sheets of spray.

Slight Influence on Life. — In the open ocean the wave doubtless has influence on oceanic life, and the breaking of the wave is certainly a means of aërating the water from which the marine organisms obtain their oxygen. Aside from this influence, the energy of the open ocean wave seems lost, excepting when encountered by vessels. The ceaseless activity of the ocean as the waves pass in succession over it, is one of the great dynamic forces of the earth's surface; and seemingly one of the least effective forces in relation to life and to earth change. Only where the waves enter shallow water and break against the shores of the islands and continents do the ocean waves exhibit their full force and enter a work of notable character. There they cause a series of phenomena which profoundly influence plant and animal life, which have distinct importance to man, and which cause great changes in the land margin, as we have already seen (Chap. XI).

Waves Due to Winds and to Pressure Difference

Similarity to Seiches. — In the chapter on Lakes it was pointed out that there are undulations of the water level, known as seiches, due to differences in atmospheric pressure on different parts of the lakes. Similar movements must be of common occurrence in the ocean, though ordinarily masked by other movements. Every time an area of low pressure passes over the water surface the level of the ocean must be very slightly raised, and with the passage of high pressure areas it must be depressed. It is quite probable that undulations of this origin are constantly passing through some part of the ocean.

Inundations accompanying Hurricanes. — When the difference in atmospheric pressure is great, there may be such a local distortion of sea level as to be plainly noticeable along the coast. Usually such a wave develops in storm centres where there is a pronounced diminution in pressure, and it progresses with the movement of the storm. Sometimes the sea level rises several feet during the passage of such storm, and low coast lands are inundated by it, causing much damage. Such was the case during the passage of the hurricane in which Galveston was destroyed in 1900, the sea level rising into the city. Other cases of inundation have been reported from the low coast lands of southeastern Asia.

Such waves, which are roughly circular, with a diameter of several score of miles, are not due solely to pressure differences. For in low pressure areas winds are blowing spirally toward the centre, and the drift of water toward the centre still further raises the sea level. Thus the wave is due to a double cause, the relative value of the two causes doubtless varying greatly in individual instances. When the pressure differences and wind velocity die down, there must be a readjustment of sea level, from which seiches-like undulations develop. There must be all gradations between extreme instances like that referred to at Galveston, and minute variations due to slight pressure differences.

Other Wind-formed Waves. — In a similar way the wind, driving water before it, must cause differences in sea level, which, with the cessation of the wind, must find adjustment. The gravitative tendency is to maintain the oblate spheroidal form; but local, temporary causes give rise to departure from this spheroidal form so long as they operate; and, with their cessation, gravity proceeds to establish the normal condition. We have less knowledge of these oceanic movements than of most other kinds, for they are irregular in occurrence, usually slight in amount of vertical range, and, excepting in the more notable instances, are masked by the other, more regular movements, yet they are known to be of common occurrence, and, as already pointed out, sometimes of very great importance because of their destructive inundations.

Other Waves

Minor Disturbances. — Waves are generated in the ocean by any pronounced disturbance of the water. For instance, a fish leaping from the water or swirling rapidly through it, or a stone thrown into the water, or a boat passing through it, are all causes for waves. The waves of a rapidly moving steamboat, for instance, may extend several miles from their source.

Avalanche Waves. — When great masses fall into the water, waves of considerable size may be generated. For instance, an avalanche falling into the water may sweep over the neighbouring coast with great force and destructiveness. Such a wave in an Alaskan fiord in 1905 rose 110 to 115 feet on the adjacent coast, and from 15 to 20 feet at a distance of 15 miles. Had the coast been inhabited, great destruction would have been caused.

Iceberg Waves. — Such avalanches are uncommon, but falls of ice from the cliffs of tidal glaciers (p. 210) are of frequent occurrence in certain localities, as in the Alaskan fiords and along the Greenland coast. There they are locally the most important kinds of waves, sweeping through the fiords every few moments or hours, according to the activity of the glaciers. Being profound disturbances of the water, these iceberg waves sweep through the fiords as low, deep undulations, which, upon reaching the coast, form powerful breakers, even when the water surface is perfectly calm.

Earthquake Water Waves. — When earthquake shocks occur on the sea floor, a wave undulation is started which affects the water from surface to bottom (pp. 433–435). This is the tsunami. Though low in vertical range, such a wave is profound, and it may sweep across the broadest of oceans. For example, earthquake waves generated on the Asiatic coast are not uncommonly recorded on the tide gauges of the American coast. After travelling such distances, the earthquake water wave has so diminished in size that it is not perceptible to ordinary observation; but on coasts near the centre of origin, as it piles up in the shallow coastal waters, it sometimes becomes a wave of great height and destructiveness, doing vast damage to life and property on low-lying coasts. Fortunately such waves are rare and local in their influence.

Ocean Currents

Causes for Currents in the Ocean. — Besides currents resulting from modification of the tidal movements, there is a complex circulation of ocean waters due to the combination of a number of causes. The following are among the more important of these: (1) The addition of water to the sea, either from the inflow of rivers, or the melting of snow or ice, or the fall of rain; (2) the abstraction of water from the sea by evaporation; (3) raising of the level of the sea surface by winds or by atmospheric pressure; (4) the drift of water before the winds; (5) change in density of the sea water, either through variation in salinity or in temperature.

All of these causes are in operation to a greater or less degree, and the water is in a constant state of movement as a result of the disturbances in equilibrium thus produced. Sometimes the movements are slight and merely local, sometimes of general extent and easily perceptible, sometimes due to a single cause, sometimes to a combination of causes. There is also a difference in significance of the several causes. For example, evaporation and rainfall, one of which tends to lower the surface, the other to raise it, operate slowly, and adjustment commonly takes place without giving rise to readily perceptible currents. Rivers, adding water to the sea, and tending to locally raise the surface, often give rise to noticeable local currents, which are, however, lost sight of in the broad ocean a short distance from the river mouth.

Melting glaciers cause perceptible currents in fiords; but these also are only local phenomena. It is, however, probable that a very notable proportion of the water that flows in surface currents out of the Arctic basin is due to the raising of sea level there by the large amount of fresh water that is poured into this basin by the rivers and from the melting snow and ice.

Importance of Wind Drift and of Density. — Two causes are apparently of greater importance in determining oceanic circulation than either of these. One of these is the drifting of water before the winds, the other the differences in density of the ocean water. If water sinks in one part of the sea, because of greater density, there must be an inflow of water to take its place. Or, if there is a drift of water away from a given area, there must be inflow to take its place; and, on the other hand, there must be an outflow of water from the area to which the water drifts, otherwise the sea level would be permanently raised.

By these disturbances in the equilibrium of the ocean waters, and the necessary adjustments to which they give rise, an oceanic circulation is caused which is world-wide in extent, and which affects the ocean from surface to bottom. The nature of this circulation can best be explained if it is considered under two distinct headings; but it must be understood that there is a complexity of causes, so that in nature there is no such arbitrary division as is adopted for clearness of presentation. These two headings are: (1) the great planetary circulation, (2) the surface wind drift currents.

The Planetary Circulation

Wind Drift, Temperature, and Salinity. — Three widespread causes are at all times at work on the ocean surface, disturbing the equilibrium of the ocean waters, and thereby inducing circulation. These are: (1) the drift of water before the winds, (2) variation in temperature, (3) variation in salinity. The other causes mentioned in the preceding section are contributory to the movements generated by these causes. It is probable also that there is a cause of circulation operating on the ocean bottom, as a result of the slow conduction of earth heat from the lithosphere to the hydrosphere.

These several causes give rise to a great planetary circulation which affects all the oceans, and water at all depths in the oceans. This circulation is slow, but general and continuous, though varying in speed and continuity. We are as yet not possessed of a sufficient body of fact to permit a determination of the relative importance of the contributing causes; nor is the course of this circulation mapped, nor its speed determined. There are, however, a number of facts which point to temperature differences as the most important factor in this planetary circulation, while the winds are the prime cause for the surface currents.

Circulation between Poles and Equator. — In the open ocean, the planetary circulation appears to consist of a sinking of cold waters in the cold temperate and polar zones, a flow equatorward along the bottom and in intermediate depths, a rising and a surface flow poleward. It may be repeated that the influence of differences in density due to salinity, the wind drift of surface water, and other causes enter into this circulation. Of the surface movements we have considerable knowledge, and that phase of the circulation is treated in the next section. The evidence of the other parts of the planetary circulation, though less direct, is convincing. In the first place, it is a well-known physical fact that cooling of salt water causes increase in density and consequent settling. This necessarily means movement away from the settling water, to give it place, and toward the point of settling, to replace that which sinks. That such movements occur there can be no doubt. That they extend widely through the oceans is proved by several facts, as follows: (1) As has already been shown, no other explanation of the cold water on the ocean bottom is possible. (2) Only by some such circulation can oxygen be moved to the ocean bottom in sufficient amount to support the life there. (3) The coldest waters are found in the parts of the ocean most open to the frigid waters, as represented in the contrast between the South and North Atlantic, and in the North Atlantic between the bottom temperatures of the eastern and western sides. (4) In the equatorial Atlantic a wedge of cold water has been found rising above the normal level, as if the water here were rising toward the surface. (5) The temperatures of the bottom of partly enclosed seas are those of the level of the lowest point in their rim, pointing clearly to a circulation by which water of the open ocean enters from the level of the rim.

Resemblance to Atmospheric Circulation. — The great oceanic planetary circulation, in general slow, but here and there accelerated for one reason or another, bears a certain resemblance to the circulation of the atmosphere, in which there is a movement equatorward, a rising there, and a poleward outflow. But there is a noteworthy difference, for while the atmosphere is warmed at the bottom, where it rests on the lithosphere and hydrosphere, the ocean is warmed only at and near the top. The atmospheric circulation depends primarily upon warming in the lower layers in the equatorial belt, with resulting decrease in specific gravity of the air and rising; while the oceanic circulation is primarily due to cooling at the surface in the higher latitudes. In both cases there is an overturning of the mobile medium, though the primary cause is different in the two cases. If the sun's heat warmed the ocean bottom, as it does the land surface, the planetary oceanic circulation would undoubtedly be much more vigorous. Such rising as results from the escape of terrestrial heat must be very slow, and it is widespread over the ocean floor, not concentrated along any given belt.

Circulation of Enclosed Seas. — The Mediterranean. — In a way the circulation in enclosed seas illustrates the phenomena of oceanic circulation. The Mediterranean may be taken as the typical illustration. It is a basin 14,400 feet deep and with a temperature of 55° from top to bottom in winter, though with higher surface temperatures in summer. It is, therefore, believed that the temperature of the deep waters is due to sinking of cold water in winter, and not to inflow of ocean water, for the water in the outside ocean at the level of the Strait of Gibraltar is above 55°. Owing to evaporation, the water of the Mediterranean is more saline and consequently more dense than the Atlantic water outside the Strait, and its surface is actually lower than that of the ocean. This condition is due to the fact that the rainfall is only about a quarter as much as the evaporation from the water surface. Since the surface of the Mediterranean is lower than that of the open ocean, there is an inflow of surface water through the Strait of Gibraltar (Fig. 413); since the Mediterranean water is denser than that of the open ocean, both because it is salter and colder, there is an outflowing undercurrent. The relative amount of outflow and inflow varies greatly according to the state of tide and other conditions; but there is a constant attempt at adjustment of the disturbed equilibrium of the connecting water bodies.

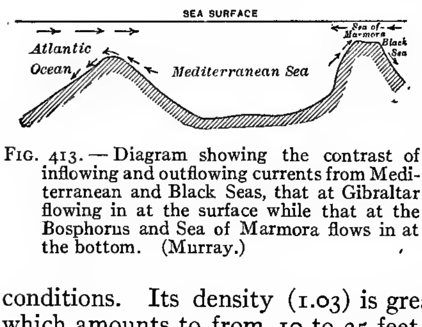


FIG. 413. — Diagram showing the contrast of inflowing and outflowing currents from Mediterranean and Black Seas, that at Gibraltar flowing in at the surface while that at the Bosphorus and Sea of Marmora flows in at the bottom. (Murray.)

Circulation in Red Sea. — The Red Sea shows similar conditions. Its density (1.03) is greatly increased by evaporation, which amounts to from 10 to 25 feet a year in a region of moderate rainfall. If there were no compensating movements of water, the Red Sea would evaporate and precipitate its salt. There is a surface current of warm water in the Indian Ocean, and an outflowing bottom current of denser water constantly passing through the Strait of Bab-el-Mandeb. It is certain that this bottom current must carry out as much salt as is brought in by the surface current, otherwise the Red Sea would grow steadily salter. That there is no inflow of water from the deeper Indian Ocean is proved by the temperature conditions. The Red Sea, which occupies a basin 7200 feet deep, with a rim rising to within 1200 feet of sea level in the Strait, has a winter surface temperature of about 70° and a summer temperature of 85° or more. Below the influence of summer warming, the water is uniformly at 70°, but in the Indian Ocean outside the Strait of Bab-el-Mandeb, the temperature is 37° at a depth of 7200 feet. There can be little doubt that the temperature of the Red Sea waters is determined by circulation in its own area.

Circulation in Black Sea. — In the Black Sea there is the reverse condition. Here the rainfall and inflow of river water exceeds evaporation, and the surface level is on the average about 2 feet above that of the Mediterranean. Therefore a surface current of less dense water flows out through the Bosphorus. A reverse current of denser water enters in the Black Sea along the bottom of the strait (Fig. 413). The reason for this current is that a column of water of such salinity as that of the Black Sea must be higher than a column of greater salinity, like the Mediterranean, if the two are in balance. That is to say, the less saline water of the Black Sea needs to stand higher than the Mediterranean water; but water is so mobile that it will flow away from a higher to a lower level, even down a grade as low as that between the surface of the Black and Mediterranean seas. This outflow therefore disturbs the equilibrium between the columns of different density, and there is a bottom inflow of saline water to restore the equilibrium. Thus there is constant outflow at the surface, and inflow at the bottom.

The Surface Currents

Causes of Currents. — Movements of the surface water of the ocean are induced by a variety of causes, such as inflow of rivers, differences in density, differences in level due to evaporation and rainfall, and to the friction of moving air. Among these causes the last is, without doubt, by far the most important, and it appears to be the chief underlying cause for the great system of surface currents and drifts of the several oceans (Fig. 416).

This cause may be imitated by blowing upon a water surface, when a miniature drift is almost immediately started. On lakes and partly enclosed seas it is a matter of general knowledge that the surface water drifts in the direction of the wind, and that the drift continues even after the impelling cause dies out, and may extend as a current well beyond the area in which the wind is blowing. Such a drift is due to the friction of moving air upon the mobile water, but it is not confined to the actual surface, for the moving surface water also drags along the layers below. Thus the wind, though operating only on the actual water surface, may start a movement which involves water to a depth of scores and even hundreds of feet.

The Indian Ocean. — In the oceans the relation of surface currents and drifts to the wind is often well illustrated, but nowhere better than in the Indian Ocean. There, in summer, the southeast trade winds extend across the equator and blow upon southern Asia as the summer monsoons (Chap. XXV); in winter the wind direction is reversed, and the winds blow off the land as winter monsoons. South of the equator the winds are fairly constant in direction, and there is a great eddy of ocean water similar to that in other oceans, as described later. But north of the equator the ocean drifts and currents are quite completely reversed in the two opposite seasons. In both seasons there is an irregular eddy in the equatorial region and extending northward into the Bay of Bengal and the Arabian Sea, but the direction of the water movement is opposite in the two seasons. In summer the water in the equatorial belt flows westward before the trade winds, then circles into the Arabian Sea and the Bay of Bengal, moving northward under the influence of the summer monsoons (Fig. 414). But in the winter the water sweeps southward out of these bays, then eastward in the equatorial belt, under the influence of the offshore winter monsoons. The east-moving equatorial current, which flows op-

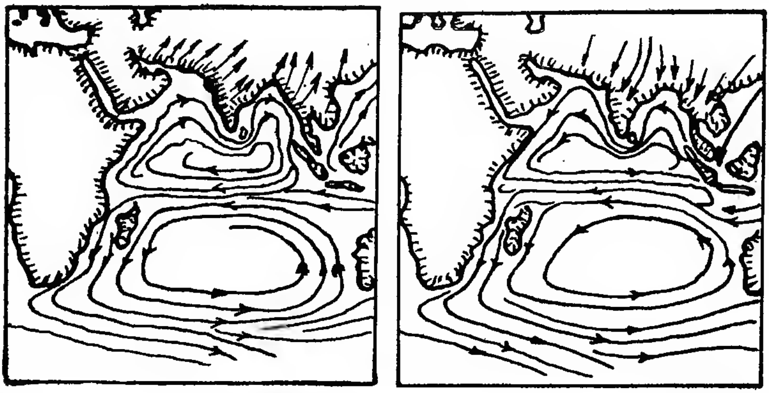


FIG. 414. — Currents of the Indian Ocean (arrows in the water) in relation to southwest monsoon of summer (arrows on land in left-hand figure) and the northeast monsoon of winter (right-hand figure).

posite or counter to the normal westward-moving equatorial currents in the oceanic eddies, is called a *counter current.*

The Southern Ocean. — Between Antarctica and the southern tips of Africa, Australia, and South America is a broad ocean belt, sometimes known as the Southern Ocean, including the Antarctic Ocean and southern portions of the Atlantic, Indian, and Pacific oceans. In the larger part of this Southern Ocean the wind direction is prevailingly from the west, and, accordingly, there is a rather regular and steady eastward drift of water, encircling the earth. Slowly moving drifts set off from this current toward the north, especially along the western sides of South America and Africa, but the great body of surface water drifts eastward with a fair degree of regularity. In a large part of the southern west wind drift there is floating ice, but it is rarely met with north of 45° south latitude.

The Atlantic Ocean. — In the Atlantic Ocean, while there are areas of variable winds and resulting wind drift currents of varying extent and direction, especially near the coasts, there are four belts of wind of sufficient uniformity of direction and persistence to generate regular drifts of ocean water. One of these is the southern belt of west winds, already referred to as the cause of the east moving current of the southern ocean. The second belt of regular winds is the northern west wind belt; the third and fourth are the trade wind belts, one on either side of the equator.

Atlantic Eddies. — In the trade wind belt the wind blows with marked steadiness from the southeast south of the equator and from the northeast north of the equator. This causes a drift of water toward the equator from either side, and, since the impelling winds are

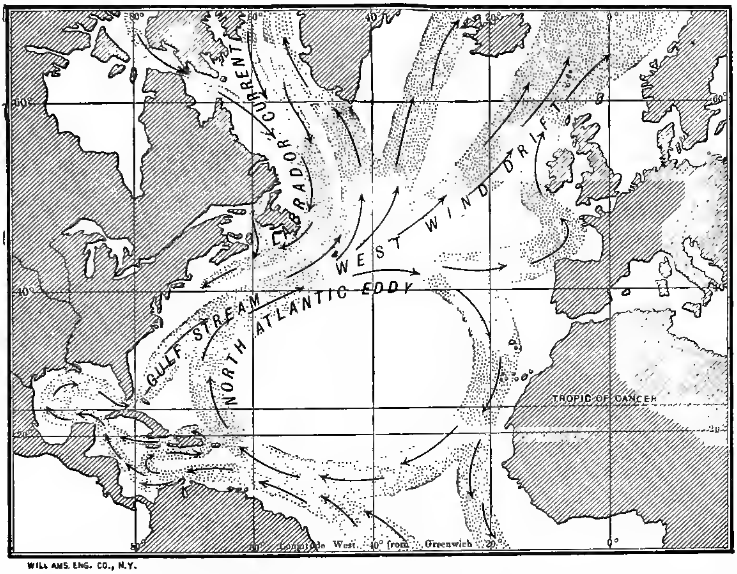


FIG. 415. — The North Atlantic Eddy, Gulf Stream, and Labrador Current. The boundaries are not really as sharp as in this diagram, and the existence of a certain portion of the Gulf Stream in the western part of the Gulf of Mexico has been questioned.

from an easterly quarter, with a westward movement toward the South American coast. Were the land not in the way, this west-moving equatorial current would probably form a west-moving drift sweeping completely around the earth. As it is, the equatorial drift divides on the South American coast, part sweeping northward, part southward. Further deflection is caused by the influence of terrestrial rotation (Ferrel's Law, Chap. XXV). The equatorial drift swings out into the Atlantic in each hemisphere, forming a great eddy in the North Atlantic by right-hand deflection, and another in the South Atlantic by left-hand deflection. On the eastern side of the eddy the water again comes under the influence of the trade winds, and thus the surface waters slowly eddy about (Fig. 415). In the centre of the eddy extensive masses of floating seaweed, or sargassum, accumulate, and this is sometimes spoken of as the *Sargasso Sea.*

While the equatorial water is in general westward movement under the influence of the southern and northern trades, there is an east-moving counter current near the centre, consisting of warm water of low salinity. This counter current may be due in part to the excessive rainfall in the equatorial belt, but it is thought to be due mainly to the return flow of some of the water that is piled up against the South Atlantic coast by the equatorial currents.

From this, it is evident that the great oceanic eddies, which are repeated in the South Indian Ocean and in the North and South Pacific, are due primarily to the motive power of the wind, but that their circular course is due to the interference of (1) the continent barriers, (2) the deflective effect of earth's rotation. Doubtless other factors of importance enter to aid in the circulation, such as the expansion of the water due to heat, the raising of the surface by rainfall in one part and lowering it by evaporation in another part, and the change in level due to the piling up of water along the coasts. It has just been pointed out that one result of this is a return or counter current at the surface. Doubtless also there is partial compensation by vertical circulation; but, with the surface water varying in density, this compensation can be only partial, since the water surface will be actually higher where less dense than in contiguous areas of greater density. Then, as in the case of the Black Sea, there may be compensating bottom movements as well as surface currents. That there is actual vertical circulation is indicated by the fact that there are cold, uprising currents along the coasts away from which the trade winds are blowing, that is, along the west-facing coasts. In this way a part of the cold water of the Peruvian Current off South America and the Benguela Current along the western coast of South Africa is accounted for. Very likely the surface drifts are also influenced by the slow upwelling of water in the great planetary circulation.

The Gulf Stream. — In the North Atlantic the oceanic circulation is complicated by important well-defined currents, some from the Atlantic, and one from the Gulf of Mexico. The latter, known as the Gulf Stream, is one of the most important of oceanic currents. It has its origin in the Caribbean Sea and Gulf of Mexico, into which a part of the equatorial drift passes by way of the Antilles and the South American coast. Here the warm tropical waters are warmed still more. Thus the level of the water in the Gulf of Mexico is raised by indrift of water and by expansion due to warming. Probably also there is additional increase in height due to rainfall and the inflow of streams from the land. It has been estimated that the surface of the Gulf of Mexico is about three feet higher than sea level at New York. Since there is a continuous submerged barrier forming the rim of the

Gulf of Mexico, there can be no adequate compensating vertical circulation, and the outflowing water must escape as a surface current, the available outlet being in the strait between southern Florida and Cuba. Thus the entire Strait of Florida is occupied by a stream of very warm, salt water, with a surface temperature of 81°, a width of about 50 miles, a depth of 1800 to 2000 feet, and a velocity of 5 miles an hour. Through the Strait it flows so fast that the bottom is swept clean of mud.

Beyond the Strait of Florida the Gulf Stream broadens rapidly, and its velocity decreases, being reduced to about 1½ miles per hour east of New York. Here the Gulf Stream waters, together with a portion of the western part of the North Atlantic eddy, is within the belt of the west winds of the northern hemisphere, and before them the warm southern water is drifted northeastward to the European coast and into the Arctic Ocean. An eastward course is also provided for by the deflective influence of the earth's rotation, which turns this current toward the right.

It was formerly the custom to speak of the warm drift of water which bathes northwestern Europe as the Gulf Stream. With better knowledge of oceanic movements it has been found that it is really a West Wind Drift in which Gulf Stream water is but a part, and the immediate propelling cause is the prevailing west winds. It might seem fitting to continue the use of the term *Gulf Stream* for this water as we continue the use of the word *sunrise*, without being open to a charge of ignorance. There has, however, been strong objection to this, some of it of a more or less pedantic nature, and the warm current on the northwestern European coast is now without a better name than the cumbersome *North Atlantic West Wind Drift.*

The Terms *Drift*, *Current*, and *Stream*. — On the ocean current map, and in the preceding description of oceanic circulation, we have made use of three terms descriptive of parts of the oceanic circulation: (1) drift, (2) current, (3) stream. There is no real distinction between these terms, though it is quite generally recognized that a "drift" is a slow motion of the upper layers without any very definite boundaries; a "current" is more rapid and more definite; and a "stream" is still more definite. The Gulf Stream, for example, is in some parts quite definitely bounded, so as to suggest a stream of warm water in the ocean. There has, however, been much exaggeration as to the definiteness of the Gulf Stream boundary. In most parts there is gradation of such slow degree that hours of steaming are necessary to pass from the normal ocean water to the unquestioned Gulf Stream water. The most definite boundary is on the western side, where a cold, south-moving current parallels it on the landward side.

A drift may move no faster than 10 to 15 miles a day, while a current or stream may attain a velocity of 4 or even 5 miles an hour. The drift is usually a broad movement, due in large part mainly directly to the wind; but a current or stream is commonly a part of the oceanic circulation, so modified as to concentrate the movement along a more or less definite belt, with consequent increase in velocity.

The Arctic Ocean. — Little is known of the movements of the waters in a large portion of the Arctic. But it has long been known that tree trunks from northern Asia have stranded on northern America, indicating a trans-polar drift of the Arctic waters. The wreck of the *Jeanette* likewise drifted across the Arctic Ocean. It was this that led Nansen on his north polar journey to push his boat into the Arctic ice with the hope that he might drift over or near the North Pole. While his boat drifted westward, as expected, it did not cross the pole, though perhaps it would have done so had he started farther east. One of the Melville-Bryant casks, placed in the Arctic Ocean near Pt. Barrow, Alaska, floated across the Arctic ocean to Iceland between 1899 and 1905, conceivably passing near the North Pole. Another of these casks drifted from Alaska to northern Norway. North of Greenland Peary found the floe ice drifting eastward, as if under the influence of the prevailing westerly winds. During the winter of 1913–14 the *Karluk* drifted westward about 800 miles from Colville River, Alaska, nearly to Wrangell Island, Siberia, moving at the rate of 7 miles a day. These furnish the basis of Amundsen's plan of drifting to the North Pole in 1915 in the *Fram*.

It is well known, however, that the warm current of the eastern North Atlantic sweeps into the Arctic north of Norway, keeping the sea clear of ice as far north as latitude 70° N., and greatly modifying the climate of northern Europe and the contiguous Arctic. There is also a north-moving current along the western coast of Greenland.

Labrador Current and other Outflowing Streams. — On the other hand, cold, ice-laden currents sweep down the coast of eastern Greenland, and along Baffin Land and Labrador. The latter, fed from between the Arctic Islands north of North America, is known as the Labrador Current, and is scarcely less important to eastern America than the Gulf Stream. Turned to the right by the deflective influence of the earth's rotation, it hugs the eastern coast of North America as far south as Cape Cod, then, continuing southward offshore, it sinks and is lost as a surface current. It is ice-laden as far south as northern Newfoundland and bears icebergs even farther south. The chill of its waters influences the coastal climate as far south as Massachusetts, and affects the water temperature even farther south, especially below the surface.

There is no really analogous current from the Arctic to the Pacific through the narrow, shallow Bering Strait. It is true that a cold current passes through Bering Strait, but although it is reinforced by cold water flowing southward from Bering Sea, it attains no such size as the Labrador Current, and does not carry its influence so far south. Nor is it ice-laden to so southern a point as the Labrador Current. Like the Labrador Current, this cold, south-moving current in the North Pacific keeps to the right under the deflective influence of rotation, and therefore hugs the North Asiatic coast and affects its climate, as the Labrador Current does that of North America, though to a less degree.

These outflowing Arctic currents doubtless represent in part a return of the water that flows in along northern Europe, in part an outflow of the fresh waters that enter the Arctic basin from the great rivers and from the melting glaciers and snows of the north. Vertical circulation to dispose of these waters is seriously interfered with by submarine ridges, which to a very large extent cut off the Arctic basin from the North Atlantic basin.

The Pacific Ocean. — On a larger scale the circulation of the Pacific repeats that of the Atlantic in its general features. There is a northern and a southern eddy, and there is a counter current between the north and south equatorial drift, extending as far east as the Gulf of Panama.

In the maze of islands in the western Pacific there is complex movement, due to deflective effects of the islands and submarine ridges, and in the North Pacific there is a current which closely simulates the Gulf Stream. This, the *Kuro Shiwo*, or Japanese Current, represents the equatorial drift, which, after entering the East Indian region, is warmed in the seas between the East Indies, the Philippines, and the Asiatic coast, and escapes as a well-defined current between the Philippines and Formosa. It passes out into the North Pacific, broadening as it flows, and by the west wind drift is propelled toward the American coast, being deflected that way also by the influence of terrestrial rotation (Fig. 416).

Since the North Pacific is nearly cut off from the Arctic, first by the Aleutian Island mountain range, then by the shallow Bering Sea, Bering Strait, and bordering lands, there is, as we have seen, no comparable south-moving Arctic current. Nor is there any escape for the warm waters drifted northwestward by the west winds. These waters, therefore, circle southward in even greater quantity than in the North Atlantic eddy. They raise the temperature of the northern Pacific and the Gulf of Alaska, but, flowing thence southward they bring cooler water off shore from the coast of United States.

The Influence of Ocean Currents

Relation to Marine Life. — The circulation of the ocean waters is of importance to ocean life in influencing its distribution, in transportation of food supply, and in distributing the needed oxygen. Without such circulation ocean life would doubtless be very different. The significance of this may be illustrated by the distribution of reef-building corals, which abound on coasts against which definite currents of sufficiently warm water sweep, while they are limited or even absent from less favourably situated coasts.

Relation to Navigation. — Ocean currents have distinct influence on navigation by aiding or retarding the movement of ships, especially

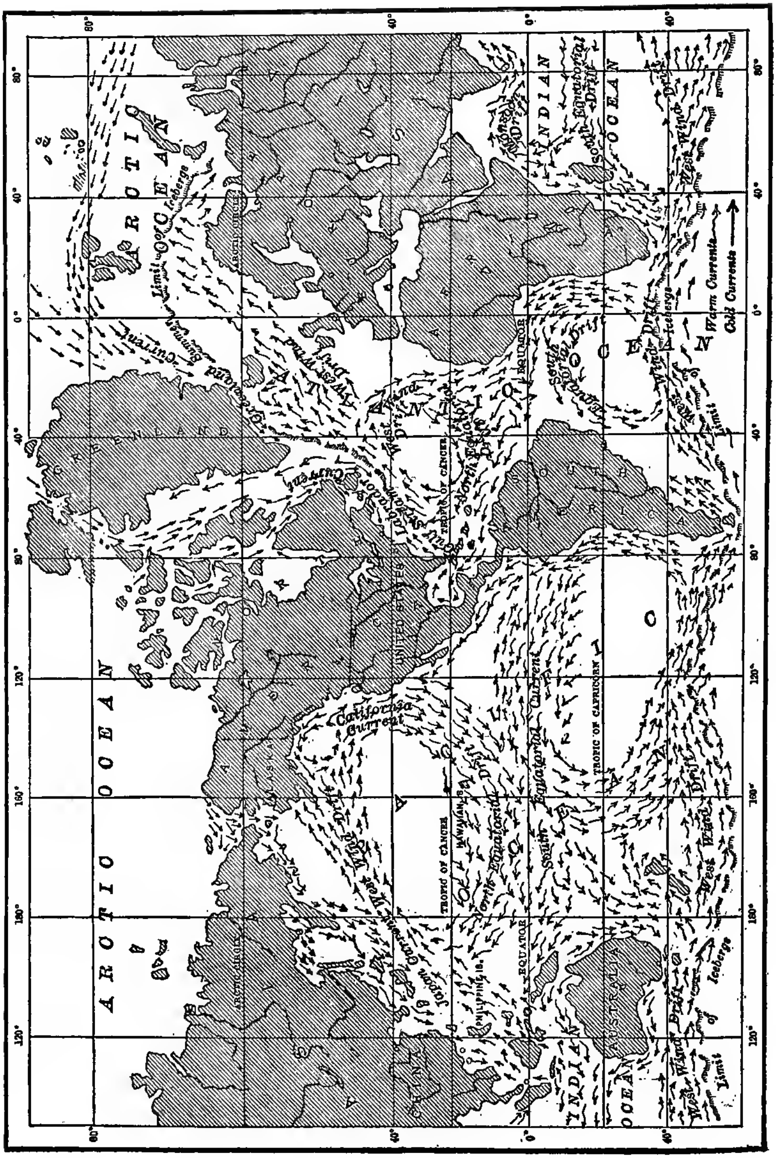
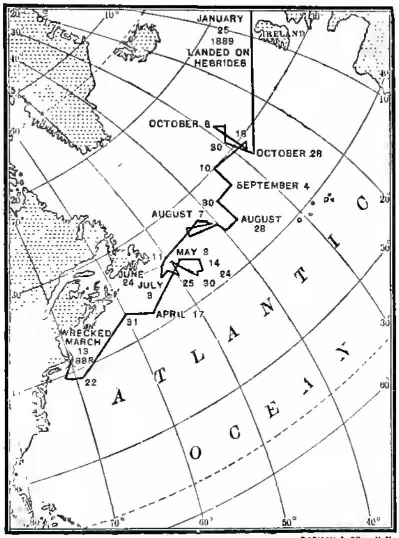


FIG. 416. — Ocean currents of the world.

sailing vessels. The strong currents along the South American coast were a very decided factor in the movement of the small ships in which Columbus sailed. Even the west wind drift of the North Atlantic produced sufficient effect upon the sailing vessels of colonial days to attract the attention of Benjamin Franklin, then postmaster-general of the Colonies. The investigation which he undertook to explain the fact that west-going boats went faster than east-going led to the first correct explanation of the Gulf Stream. It goes without saying that a current flowing at the rate of 4 or 5 miles an hour, as the Gulf Stream does, is a factor to be reckoned with in navigation; and even the slower drifts are of importance. The accompanying diagram (Fig. 417) showing the drift of a derelict, illustrates both the direction and rate of movement of an object at the mercy of wind, waves, and currents in the North Atlantic. Many observations have been made on floating derelicts, and on bottles placed in the ocean for the purpose, in order to determine the rate and direction of the ocean currents and drifts.



BORMAY & CO., N.Y.

FIG. 417. — The path of a wrecked vessel which drifted across the Atlantic in ten months, being occasionally turned back by storms.

Relation to Climate. — The outflowing water from the Arctic and Antarctic regions is of great importance in modifying the climate of those regions, for the cold water that sinks to the bottom creeps to other zones, and the surface currents carry both cold water and ice to warmer regions. Without such distribution of cold water and ice the conditions in the polar zones would doubtless be far different. Every season vast quantities of sea ice and glacier ice are drifted out of the Arctic. These cold surface currents naturally affect the temperature of the sea in the regions to which they flow, and the winds which blow over them are chilled in their passage. Since the deflective effect of rotation swings these currents against the east-facing coasts of the northern hemisphere, their influence is mainly felt in the western parts of the ocean and the contiguous east-facing lands. The cold climate of Labrador, Newfoundland, and New England is in part due to the effect of the cold Arctic current transmitted to the land by the ocean winds.

The warm currents produce influences essentially the opposite of those caused by cold currents. They distribute the tropical heat and diminish the temperature of the tropical waters. Partly enclosed seas, like the Red Sea, the Mediterranean, and the Gulf of Mexico, have higher temperatures than the open ocean in the same latitude, partly because of the lack of opportunity for distribution of the heated water. We may be certain that without ocean currents the temperatures of the tropical waters would be far higher than they are. This warmth is distributed in the great oceanic eddies well up into the temperate zones, and in the North Atlantic even into the polar zone. The effect of rotation swings these currents to the eastern side of the ocean, so that the west-facing coasts are bathed by warmer currents, as is so well illustrated on the northwestern coasts of North America and Europe. The winds blowing over these warm waters produce a profound influence upon the contiguous lands. Thus Europe is inhabited by an agricultural population up to the Arctic Circle, while in eastern North America a bleak, barren land is found in the same latitude as flourishing farm land and dense industrial population in Europe.

Relation to Rainfall and Fog. — The ocean drifts and currents have also important influence on precipitation. Winds blowing over warm waters become charged with vapour, and this is, of necessity, partly precipitated when the air is chilled either in passing over cooler water or in rising over the land. It is due to the latter cause that there is so heavy a rainfall on the western coasts of Europe and America; while the former cause explains numerous fog belts. One of the foggiest places on the earth is on and near the Banks of Newfoundland, where the warm southern current and the cold Labrador Current flow side by side in opposite directions. A vessel rarely crosses this region without encountering fogs. At San Francisco and offshore from it fogs are common, because a cool south-flowing current exists immediately offshore, while beyond is warmer water over which the winds blow, obtaining abundant vapour which is condensed into fog particles as the air is chilled in the passage over the cold current.

Tides

Distortion of the Hydrosphere. — Both the sun and the moon exert an attraction on the earth, as a result of which the liquid hydrosphere is distorted, and this distortion causes the phenomenon of tides. It is too complicated a phenomenon for complete discussion in a book of this scope, requiring for its adequate treatment mathematical discussion. Those desiring to read more about this should consult a textbook of astronomy, the Encyclopædia Britannica, or the reports of the U. S. Coast and Geodetic Survey.

Lunar Distortion exceeds Solar. — Since the attraction of gravitation varies with the mass and inversely as the square of the distance, the moon, 240,000 miles distant, although so small, has far greater tide-producing power than the larger sun, 93,000,000 miles distant. If there were no moon, there would still be a tide, though much smaller and much less complex than the present tide, whose main characteristics are dominated by the moon. We, therefore, commonly speak of it as the lunar tide, though it must not be forgotten that the tidal movement is a complex combination of lunar and solar tide.

The moon distorts the hydrosphere, raising a broad swell on the surface nearest the moon, and another, somewhat lower, on the opposite side of the earth, while between these two swells are broad depressions or troughs. If the earth were completely liquid, this distortion would be in the nature of an ellipse. A similar but lower distortion is caused by the sun. As the earth rotates, this distortion follows the inciting cause. It therefore sweeps around the earth once in about twenty-four hours, so that two solar and two lunar waves, with intervening troughs, pass around the earth approximately during each rotation.

The passage of these tidal waves is subjected to a complex series of modifying influences. Some of these are due to irregularities of ocean bottom and coast, others to astronomical causes, such as varying distance between earth and moon or sun, and varying relative positions of earth, sun, and moon. Therefore the tide varies greatly, both in interval and in height; and both in a given locality and in different localities.

Period between Tides. — The tide does not coincide exactly with the moon's position, but lags behind it. Nor does it sweep around the earth in a general wave; but apparently develops in the different oceans, as it does in small degree in large lakes and enclosed seas, for the lands stand in the way of the free sweep of the tidal wave. In its passage around the earth the tide does not recur at the regular interval of half a rotation, 12 hours, but in half a rotation plus the forward movement of the moon in its orbit around the earth, or 12 hours and 26 minutes. Thus there is a retardation of 26 minutes between each tide or 52 minutes in the day, so that if high tide comes at 12 o'clock noon on one day, it will appear at 26 minutes past 12 that night, and at 8 minutes before 1 o'clock the next noon.

Height of Tides. — The exact height of the tide in the open ocean is not known, and doubtless varies from place to place, as it certainly must from time to time. It is not a recognizable movement of ocean water in the open ocean, though on oceanic islands it registers itself as a slow rise and fall of the ocean surface twice each day, and to a height of 2 or 3 feet. The highest reach of the water is called *high tide*, the lowest reach *low tide* (Fig. 418), and when the tide is rising it is commonly said to be coming in or flowing, since the rising water advances upon the land. The falling tide is said to be going out or ebbing. The motion is really that of two great waves, with broad, low crests and intervening troughs, sweeping through the ocean and causing a slow, rhythmical rise and fall of the surface, while the entire ocean water from surface to bottom is involved in the motion.

FIG. 418. — High tide and low tide near Bourne on the coast of Massachusetts. (J. L. Gardner.)

Varying Relationships to the Moon. — The range between the sea level at low and high tides, known as the *tidal range*, is subject to considerable variation according to the distance of the moon. When in its orbit around the earth, the moon is farthest from the earth, or in apogee, the tidal pull is less than at the opposite parts of the orbit, or perigee. There is, therefore, a rhythmic variation in tidal range, with a period of about two weeks between the higher or perigee stage and the lower or apogee stage. Since the distance between earth and sun also varies during a complete revolution, being nearest in the perihelion and farthest in aphelion, there is a similar, though slighter, semi-yearly variation in the solar tide. The tidal range is also influenced by the position of the moon in the heavens, for with the change in season the moon is vertical at different latitudes, and since the ocean water is disturbed irregularly over the earth, the variation in influence of lunar pull is very considerable.

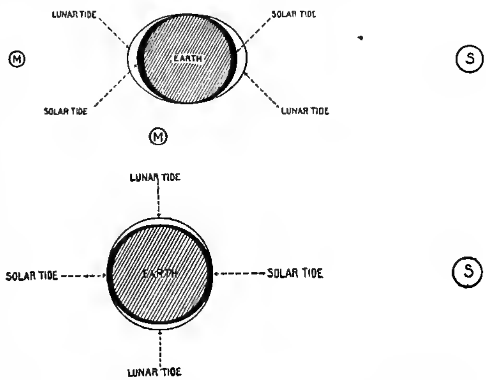


FIG. 419. — Diagrams to show positions of moon and sun at spring tide (above) and neap tide (below).

Even more noteworthy than these causes for variation in the height of the tidal wave is the relative position of sun and moon. When the sun, moon, and earth are in nearly the same line, the solar and lunar tides are combined, and the tidal range is high. These high ranges of tide are known as *spring tides*, and they occur at new and full moon. The opposite condition, when moon and sun are out of line, occurring in the periods of the moon's quarters, give rise to a lower range of tides because the solar and lunar tides are not combined. These are known as *neap tides*. Therefore once each lunar month there are two spring and two neap tides (Fig. 419).

To go much farther with a statement of tidal variation would demand mathematical treatment. Enough has been said, however, to indicate the main fact of great variability in inciting cause. Summarized, we have (1) a daily, 24 hour and 52 minute rise and fall of the ocean surface with two periods of high and two of low water, the range of one of the tides being greater than that of the other; (2) twice each lunar month the range is higher than normal — spring tides — and twice lower — neap tides; (3) the range varies also with distance between earth and moon, between earth and sun, and according to the latitude where the moon is vertical; (4) the tidal range varies with different combinations of these causes for variations. It is, therefore, an exceedingly complex phenomenon that is included under the term *tide*.

Varying Relationships to the Lands. — Even greater complexity is introduced by the complex environment in which the tidal movement takes place. There is, first of all, the fact that the ocean waters are irregularly distributed, and that they are separated by lands and by submerged ridges. It was formerly postulated that the tide was generated in the great southern ocean and that it swept up into the Atlantic, Pacific, and Indian oceans, advancing successively to more and more remote parts of the branching oceans. The movement is now found to be much more complex, and it is thought by some students of the subject that the tide is generated in the main in the individual oceans. The exact mode of origin of the tidal waves, and the relation of the tidal wave of one ocean to that of another, is not yet clearly demonstrated.

A second important influence of environment is the effect of shallowing water. Every continent is surrounded by a continental shelf, and, as the profound tidal movement reaches this shallowing area, it is increased in height. Thus there are few places on the exposed coasts of continents with a tidal range as low as 2 or 3 feet. It is quite possible that the assumed height of the ocean tide from measurements on oceanic islands is also somewhat too great because of piling up of water as the tide advances upon the islands. Where the influence of shallowing water is most felt, the tidal range may become as much as 5, 10, or 15 feet, and in limited areas even more. At the same time that the tidal wave is thus locally raised, horizontal movement is also frequently introduced, causing tidal currents. These are common in the shallow waters surrounding most continents, and they are also proved to exist in shallow areas in the open ocean. Such tidal currents are not properly the tidal wave, but a modification of it by interference with the wave motion due to shallow water.

There is, thirdly, a very complex modification of the tide by the irregularities of coast lines. This subject is so complex that a complete analysis of it is impossible here; but a general view of the influence of this cause may be gained by selecting a few typical instances.

Tides in Partly Enclosed Seas. — Along many coasts there are bays with the entrance more or less enclosed. The Mediterranean, for instance, is open to the sea only by a narrow strait. When the Atlantic tide rises outside the Straits of Gibraltar, there is an inflow of water into the Mediterranean; but manifestly this cannot be sufficient to cause tidal rise and fall in so large a sea. Therefore there is no tide in the Mediterranean, excepting a very small one generated in this sea itself. A more open bay, like the Gulf of Mexico, is less isolated, but even here the open ocean tide causes only slight rise and fall. A very small bay, with a narow opening, can be filled as the tide rises, and lowered as it falls, but a large bay cannot be. In each case, however, powerful tidal currents flow through the narrow opening as the outer ocean level varies.

Tides in Broadly Open Bays. — On the other extreme, there are many bays with broad mouth and narrowing toward the head. Into these the tidal wave advances, and its height is increased not merely by interference due to shallowing bottom, but also by the convergence of the margins. It is in such places that we get the greatest tidal range, as in the Bay of Fundy, where there is a range of from 30 to 53 feet, in Ungava Bay, where there is a similar tidal range, and in Turnagain Arm of Cook Inlet, Alaska, where the vertical difference between high and low tides is 54 feet.

Tidal Races. — Between the two extremes of broad-mouthed and narrow-mouthed bays there is every intermediate form, and each has its own influence upon the tidal wave. Accordingly there is great variety in the tidal range, even within narrow limits. There is also variation in the time at which high or low tide reaches points, for as the wave advances upon an irregular coast it reaches the headlands first, then progresses into the indentations at a rate varying with their form and depth. On very irregular coasts it therefore sometimes happens that the tide is high in one bay at a different time than in a contiguous bay. If a strait connects such bays, rapid currents or *races* sweep through them with both rate and direction varying with the state of the tide. Or the same condition may be the result of the fact that in one bay the tide rises higher than in the other. Such races often occur in the gap between New York Bay and Long Island Sound at Hell Gate; also in the straits between Buzzard's Bay and Vineyard Sound, especially at Wood's Hole. Rapid currents develop also in the Bay of Fundy, in the English Channel, and the North Sea, along the coasts of Alaska, British Columbia, and Norway, and in many other places (Figs. 420, 421).

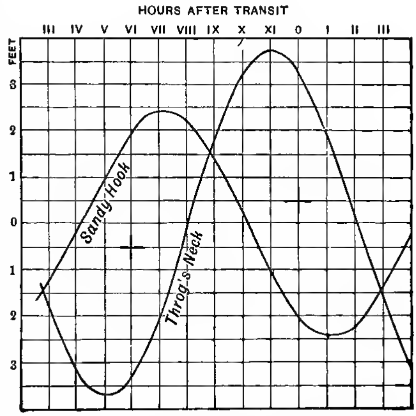


FIG. 420. — Different time of arrival and different height of tide on the two sides of Hell Gate near New York City. (U. S. Coast and Geodetic Survey.)

These currents often become very rapid and complex, even interfering with navigation. Where such currents develop, they may flow side by side in different directions, or at different rates, or one current can flow above another. The water is set into rapid and irregular motion, increasing during some stages of tide and decreasing during others. At dead low or high tide they may nearly or quite cease, and the direction of motion during the incoming tide is reversed during the outgoing tide. Where such currents develop, the terms *coming in* and *going out* are much more applicable than on more open coasts where there is little if any current but a gradual rise and fall of the oceanic surface. Even where the tidal currents exist, however, the surface gradually rises and falls with the tide.

In favourable localities the tidal currents develop a rough choppy wave surface known as the *tide rip*, which is greatly intensified when the wind blows against the current. Sometimes the rip is due to friction with a shallow bottom, but at times it occurs where the water is too deep for that explanation. In such cases it seems to be due to friction of the surface current with the lower layers which are either stationary or flowing in a different direction.

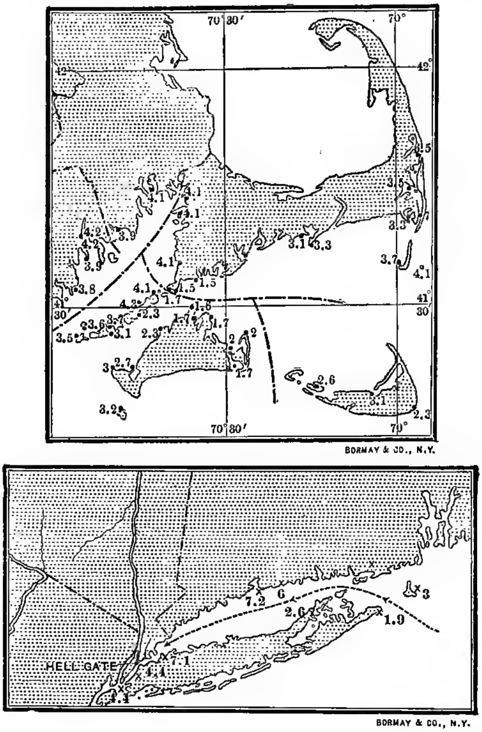


Fig. 421. — The high tides in Buzzard's Bay, Massachusetts, and in Long Island Sound, in contrast with the lower tides near Martha's Vineyard Island and in New York harbour. This inequality of level results in tidal races between the islands south of Buzzard's Bay and at Hell Gate.

Tidal Influence in Fresh Water. — Where the tide enters river mouths, the salt water extends up a certain distance, depending upon the slope of the river bed, the height of the tide, and other factors. But the tidal effect reaches still higher, for the salt water dams the stream, holding back its current, and causes a tidal rise even in the fresh water. In large streams this effect may extend 100 miles or more up-stream. In the St. Lawrence the tide is felt nearly to Montreal and in the Hudson above Albany. In such long, narrow stretches the tide is usually unequal, the high tide coming rather quickly, while the period of low tide is prolonged. With considerable bodies of fresh water thus ponded back, the outflow after the high tide stage is naturally extended. And the time of high and low tide is not simultaneous with that at the river mouth, for an interval is required for the tidal effect to pass up-stream. But even with such causes for variation there is a rhythmic swing of tidal rise and fall here as elsewhere.

The Bore. — A peculiar modification of the inflow of the tide in estuaries on coasts with a high range is the *bore*, as illustrated in the Petitcodiac River, New Brunswick (Fig. 422). Here the tide rises high in the Bay of Fundy, and during the low water stage the " river," or estuary, is a broad mud flat, bordered with marshes and with only a small stream flowing down it. The tide rises into the estuary, but it cannot advance up it as fast as it rises in the open estuary mouth. There is, therefore, such a difference in elevation between the sea level in the estuary mouth and the floor of the estuary higher up that the water breaks into a wave with foaming crest, which rushes rapidly up

FIG. 422. — The bore, at Moncton, New Brunswick.

the estuary. Day after day this bore wave rushes up the river at the proper stage, and with such regularity that its period of arrival is predicted within a minute or two. It varies in height according to the tide in the bay, but, even when lowest, is an impressive sight. After the arrival of the bore the water flows rapidly in, and high tide is soon reached. The rise is so rapid that one can see it rise on the shores.

Similar bores occur in other places, differing in height and in detail from this one, but in essential features being similar. Among the places where the bore occurs are the Severn in England, the Seine in France, the Amazon, and some of the Chinese rivers. In some of these cases the bore appears only at certain states of the tidal wave and not with the regularity of the Petitcodiac bore. In the Seine the bore is known as the *mascarat;* in the Amazon as the *powcoa.*

Where developed as a high wave, as in China, the bore is sometimes very destructive, and special means are taken to protect the shipping and the river banks from its effects.

Tidal Prediction. — From the preceding it is clear that the height of the tide varies from time to time and from place to place, and that there are also variations in the time between tides, and in the behaviour of the tidal rise and fall from mere surface swing to rapid currents and even to the tidal bore. There are places where there is no tide, or only one tide, or one high range and one low range, or one long and one short tide. Yet, in spite of all these variations, there is such underlying regularity that it is possible to make accurate predictions for any place on the earth. It is, however, first necessary to know the local influence, and this requires a series of observations. But having made these observations, since the regularly recurring cycle of rise and fall will be repeated rhythmically, a series of accurate predictions can be made for years in advance by taking into account the various astronomical causes for variation. The local influences are constant for a given locality; the astronomical causes for variation are regular and calculable. Therefore, knowing the local peculiarity, and understanding the astronomical causes, gives the necessary basis for tide prediction both as to time and range. It is on this basis that tide tables are prepared for all parts of coasts visited by ships of civilized nations.

Importance of Tides to Man. — Tides and tidal currents are among the most important phenomena of coast lines, but in the open ocean are of little importance. The time and height of tide must be reckoned with in all navigation near the coast, and the force and direction of tidal currents must be known. Often vessels are drifted out of their course by the tidal currents, and these are among the most frequent causes for shipwreck. The tides are important in coastal cities as a means of removing waste products and as a cause for maintaining a supply of pure salt water. Without the efficient aid of the tides the problem of life in seaport towns would be much more serious than it is.

Tidal currents are important means of distribution of sediment, and, as we have seen, are factors of significance in the development of coast lines. By them sediment is often drifted into and across bay and harbour mouths, and one of the problems of civilized nations is how best to combat the tidal influence, which is helping to seal up harbours with sediment. The building of jetties, dredging, and other means are being employed by commercial nations, with an annual expenditure of millions of dollars, to combat this phase of tidal work.

The tide, like the ocean waves, represents a vast store of energy, most of it apparently going to waste. In a very few places dams have been made to impound the water of the high tide stage, but, with this exception, man has made no direct use of this vast store of energy expending itself along the continental coasts.

For references to literature, see pp. 665–668.

PART III. THE ATMOSPHERE

CHAPTER XXII

CHARACTERISTICS OF THE ATMOSPHERE

General Description

Relation of Atmosphere to Earth. — The earth is enveloped by a gaseous mantle known as the *atmosphere*, though the substance of which it is composed is usually called the *air*. The atmosphere is quite as much a part of the earth as are the solid rock and the water of the oceans and rivers. It contains the same elements as those which make up the land and sea, only it exists in the gaseous instead of the solid or the liquid form, just as water may exist as solid ice, liquid water, or gaseous water vapour.

The atmosphere, as we know it, is quite different from that other transparent substance which separates the earth from the sun, stars, and planets and which is called the *ether*. The atmosphere travels with the earth on its journey around the sun, being held in place through the earth's attraction of gravitation.

Thickness of the Atmosphere. — The thickness of the earth's atmosphere is not known, but we do know that the part of the atmosphere which is dense enough to support life is limited to about 5 or 6 miles from the earth's surface. Aviators in aeroplanes have ascended to a height of over 4 miles. The atmosphere, however, in more or less modified form, extends higher than the loftiest mountain top (Mt. Everest, 29,002 feet or about 5½ miles). The ascent of balloons has shown that it extends even higher. Balloons with aeronauts have been over 6 miles from the land surface. No ascents of this sort have been made over the oceans. Unmanned (sounding) balloons have been up to an altitude of about 18 or 20 miles. The phenomena of twilight indicate that the atmosphere extends to a height of at least 45 miles. The glowing of meteors at an elevation of nearly 200 miles above the earth's surface shows that the atmosphere is present there, for, in the ether of space, meteors do not burn. It is thought from the lights of the aurora that the atmosphere is present over 200 miles above the earth, though at this height it must be extremely attenuated.

Atmospheric Pressure

Density near Earth's Surface. — The weight of the atmosphere at sea level is about 15 pounds to the square inch, the equivalent of about 34 feet of water or 30 inches of mercury. This is because the air, although light and invisible, has perceptible weight; and each particle, drawn down by gravity, presses on those below it, as stones in a pile press on those beneath. The air, extending to a height of 200 or more miles above the earth's surface, has a weight which can be measured. The average weight at sea level is convenient for use as a unit. We, therefore, say that the weight of air on each square inch of sea level is about 15 pounds.

Every square inch of the surface of the human body bears a great weight of air. The pressure within the body, however, is equal to that outside, so that we do not notice this pressure. If the outside pressure were suddenly removed, the expansion of the air within our bodies would probably burst many of the tissues and cause the eyes to protrude and the skin to crack, as is the case with fish which are hauled up from the deep sea, where they were under great pressure of water, to the surface, where this pressure is relieved (p. 650).

The column of air resting on the top of a mountain a mile high is of course 5280 feet less in height than a similar column (Fig. 423) at sea level, and, therefore, of such diminished weight that the atmospheric pressure on the mountain top is less than that at sea level. Pressure pushes the molecules of a gas, such as the atmosphere, closer together, so that the air is denser near the sea than on mountain tops. Accordingly, fully two-thirds of the atmosphere, by weight, is within 6 miles of sea level, and the air is not nearly as dense at the top of a high mountain, like Mount McKinley or Mount Everest, as it is at sea level near the base. On mountain tops the thinness or rarefied character of the air is such that it is difficult to breathe enough oxygen for the needs of the body. Some men and animals accustom themselves to this rarefied air so that they are able to live on high plateaus and mountains; but the rarefied air furnishes the principal reason why the higher mountains of the world have not yet been ascended. Persons living at the lower levels, however, find that when they are on mountains they must breathe more rapidly in order to get enough oxygen, and frequently they become exhausted in the effort. It is also difficult to sleep at great altitudes.

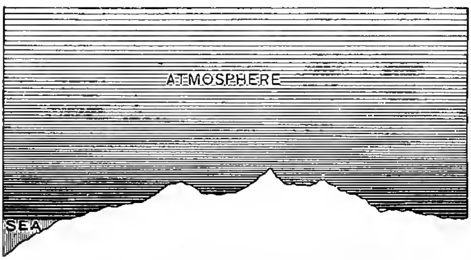


FIG. 423. — Diagram to show why the atmosphere is more dense at sea level than on a mountain top.

Relation to Temperature. — Because of the elasticity of air, its weight or density also changes with difference in temperature. The air filling a room 10 by 20 feet weighs 301 pounds when the temperature is 60°. When the temperature is increased to 80°, the air is so expanded that some of it will be expelled from the room if opportunity is given, and the amount left in a space of this size weighs only 291 pounds.

Relation to Gravity. — Because of the different pull of gravity on light air and on heavy air, atmospheric movements are started; and this movement of air from place to place is known as wind (Chap. XXV).

Barometric Pressure. — The temperature at the earth's surface is always changing and, consequently, the weight of the air changes also. This weight or pressure of the air is measured with an instrument known as the *barometer;* and the weight of a column of air at any given place is known as *barometric pressure.* The barometer takes advantage of the principle that atmospheric pressure will push the liquid up into a tube having a vacuum in the top, displacing it until a column is formed that equals the weight of the air column pressing on it. This pressure, for example, pushes water up from a well into the tube of a pump. The stroke of the pump exhausts the air from the tube, tending to make a vacuum into which the water may be pushed by atmospheric pressure. Because of the fact that a column of water 34 feet high balances the air pressure, an ordinary pump cannot raise the water from a well more than about 34 feet deep.

Mercurial Barometers. — Barometers can be constructed with water columns a little less than 35 feet long. Usually mercury is employed in the tube, because it takes a column of mercury only 30 inches high to balance the atmospheric pressure.

A rough barometer may be made by using a glass tube about 35 inches long, sealed at one end. If the tube is filled with mercury and inverted with the open end in a small dish of mercury, the mercury in the tube will first fall a few inches and then remain stationary, being kept there by the air pressure. By fastening the tube to an upright stick it is possible to watch the mercury rise and fall from day to day with the variations of atmospheric pressure. If a scale is marked on the glass of the tube, the amounts of variation may be roughly measured. With the coming and passing of storms there is a variation in atmospheric pressure. This is recorded by the height of the mercury column, which is measured in ordinary mercurial barometers in inches and tenths of inches, or, with a scale called the *Vernier,* in hundredths or thousandths of inches. When the air is heavy, the column of mercury in the barometer is high; 30.20 inches for example, is a relatively high barometer. With light air the column of mercury in the barometer is low, but the range between high and low pressure for a given altitude is slight, and 29.30 inches is a relatively low barometer. However, 30.20 inches is not always to be regarded as HIGH, nor 29.30 inches as always LOW, for high and low barometers are not associated with definite fixed values.

Aneroid Barometers. — Because of the disadvantage of carrying a mercurial barometer, another instrument, called the *aneroid barometer,* is more often used. An aneroid, as usually made, is small enough to be carried in the pocket and has a metal diaphragm inside a metal case. The differences in air pressure cause this diaphragm to move, and the movement is communicated to a hand which moves over a dial.

Use of Barometers in Measuring Elevations. — Because there is less air and, therefore, less pressure above plateaus and mountains than above plains, the barometer is low on highlands and high on lowlands. This makes it possible to use the barometer in measuring elevations. By graduating the dial in feet, it is possible to measure changes in elevation with an aneroid barometer. A disadvantage in the use of any barometer for measuring altitudes is that it is affected not only by variations in pressure measured by a person who travels from lowlands to highlands, but also, as is explained later, by (*a*) changes in air pressure during the passage of storms, and (*b*) those due to the heating of the atmosphere. In using a barometer for the accurate measurement of elevation, therefore, it is necessary to compare its record with that of another barometer which is kept at a fixed point, and to make corrections accordingly.

Barographs. — Another form of barometer, the *barograph,* is self-recording, having a pen point continuously pressed against a cylindrical roll of paper which is revolved by clock work. The barograph gives a continuous record of changes in atmospheric pressure (Fig. 447).

Composition of the Atmosphere

The Atmospheric Mixture. — The atmosphere is a mechanical mixture, not a chemical compound. The most important components for our study are, (*a*) oxygen, (*b*) nitrogen, (*c*) carbonic acid gas, (*d*) water vapour, and (*e*) dust. Of these, oxygen and nitrogen make up the greater part, and the air is chiefly a mixture of these two gases, about 21 per cent oxygen and 79 per cent nitrogen (Fig. 424). In 1894 argon, and, subsequently, several other inert new elements were discovered in the atmosphere. They are so much like nitrogen that the discovery of their presence does not change our views regarding the behaviour of the atmosphere in any essential way.

Oxygen. — Oxygen is a necessary element in the atmosphere for man and all animals. Man could not live in an atmosphere of pure oxygen, and it is, therefore, important that the oxygen be diluted with the nitrogen, for otherwise the rapid changes we know as *combustion,* and with which we are familiar in connection with the burning of a fire, would cause rapid changes in the tissues of the body and make it impossible for men and animals to live.

Nitrogen. — Nitrogen, in addition to its importance in diluting the oxygen of the air, is used by some plants.

Carbon Dioxide. — Carbonic acid gas, or carbon dioxide, forms only 0.03 per cent of the air under ordinary conditions, but is exceedingly important. It is composed of one part of carbon and two of oxygen, and plants have the power of separating these two gases, building the carbon into their tissues and releasing the oxygen to be breathed by men and animals.

In the bodies of animals, oxygen unites with carbon by a process of slow combustion, so that, with every breath, we exhale a small quan-

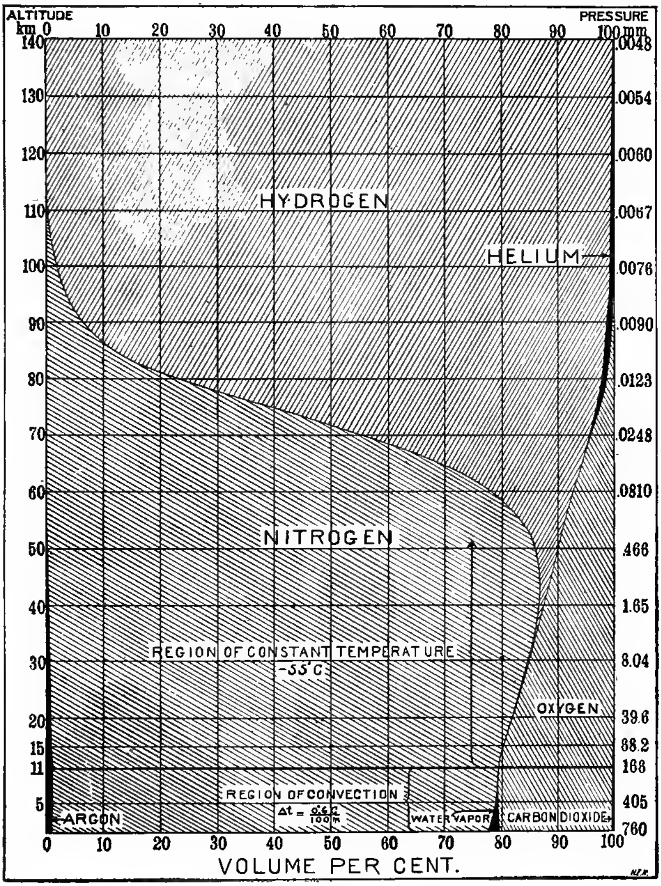


FIG. 424. — Proportions of the atmospheric gases at the earth's surface, and calculation of change with altitude. (Humphreys.)

tity of carbon dioxide, which is a poisonous gas. In such a rapid form of combustion as fire, the oxygen combines rapidly with the carbon of the wood, or coal, or oil, and produces heat. This we use to form steam in locomotives or engines which run machinery. It is likewise true in the slow combustion within the bodies of men and animals, that heat is formed, producing some of the energy which animals need for life.

Water Vapour. — It is a familiar fact that water vapour is taken as an invisible gas from the surfaces of water bodies, so that a pool of water evaporates under the heat of the sun, and a dishful of water is converted into water vapour on the surface of a stove. Likewise the wet surfaces of sidewalks become dry when the air is moving over them, even if the sun is not shining, and wet clothes which are hung on a line become dry because of the *evaporation* of the water. This process of evaporation constantly introduces water vapour into the atmosphere, but the amount of water vapour varies from place to place, so that some places have very dry air, while others have damp or humid air. Likewise, the amount of vapour differs in the same place from time to time, some days being dry, others humid. Evaporation in dry air is rapid and is usually accompanied by a clear sky, but when there is much vapour there may be clouds and rain. Such forms of water as dew, frost, fog, clouds, rain, snow, and hail (Chap. XXIV) are due to the condensation of the water vapour in the atmosphere.

Dust. — The solid particles that float in the air are known as dust. Dust is introduced into the air (*a*) from chimneys and from forest fires, in the bits of carbon which we call smoke, (*b*) in small particles of pollen from plants, (*c*) in the dust that blows up over dry places, (*d*) in the fine particles which are thrown into the air from volcanoes, (*e*) in the salt from the oceans, and (*f*) the meteoric dust that comes from the burning and disintegration of shooting stars.

Around cities, dust particles are exceedingly abundant because of the large amount of smoke which rises from chimneys. Thus a dull, hazy atmosphere is exceedingly common near large centres of population. During periods of drought, the roads and fields in the country contribute a good deal of dry material which may float away in the air. Accordingly there are times when the air in the country becomes as hazy with dust as in the vicinity of the cities. The dust is washed from the air in rain storms, and on this account it is usually clearer after a rain. Upon high mountains and over the ocean the air is fairly free from dust particles. Although dust is everywhere present, and while it is invisible under ordinary circumstances, it may be seen clearly when a beam of light shines into a darkened room. There are, of course, quite as many dust motes floating in the air everywhere as are seen in the beam of sunlight, but they are not visible under ordinary conditions.

The dust in the atmosphere furnishes solid particles around which the water vapour condenses to form fog and rain, and gives us the colours of the sky, and the phenomenon of twilight. Microörganisms are also included under the general term, atmospheric "dust," and these are often related to the occurrence of disease.

For references to literature on General Characteristics of the Atmosphere, see pp. 744–745.

CHAPTER XXIII

LIGHT AND WARMTH IN THE ATMOSPHERE

Light in the Atmosphere

The Nature of Light. — It is a familiar fact that the light of the earth is supplied by the sun and is transmitted through the 92,750,000 miles from the earth to the sun at great speed, traversing this distance in about 8 minutes. Light is also emitted by other bodies having high temperature, for example, by burning coal and red-hot iron.

Colours of the Rainbow. — Sunlight travels in a series of waves, which differ in length and colour, but whose union forms white light. When a beam of sunlight is passed through a glass prism, these light waves are turned, each at a slightly different angle. The sunbeam enters the prism as white light, but comes out of it with the colour waves separated, so that violet, indigo, blue, green, yellow, orange, and red may be recognized. These colours are known as the *colours of the spectrum*, or, because of the fact that the light waves are similarly separated in the drops of water of a rainbow, the *colours of the rainbow*.

Refraction and Selective Scattering. — The bending of the rays of light is known as *refraction*. In their passage through the atmosphere the waves of light are interfered with by the dust and water in the air, and colours are, therefore, produced. The dust in the air produces colours through *selective scattering*, the dust in the air interfering with the passage of light waves, as small pebbles in shallow water interfere with water waves. The dust thus causes some of the waves which make white light to be turned aside or scattered, and the waves having the shortest length, those in the violet end of the spectrum, are most easily turned aside. That is, they are selected for scattering.

Because of this selective scattering of the short blue waves the sky has a blue colour. There is a great deal of dust in the air, however, and the more dust, the greater the loss of the blue, and hence the greater the predominance of the reds and yellows, giving the sky the red and yellow colours, as at sunrise and sunset when the rays of light pass through a great thickness of the lower, dust-filled layers of the air (Fig. 425). The varied colours of clouds at sunrise and sunset are mainly a result of the reflection of colours caused by refraction and selective scattering.

Reflection. — The phenomenon of *reflection* of rays of light from a body is familiar in the reflected light from smooth surfaces, like water or the glass of a mirror; but irregular surfaces like the ground also reflect light, and it is reflected sunlight which makes the moon appear to give light. The earth would have the same appearance if seen from the moon; and some of the other planets have their light for the same reason. The stars, however, give light as the sun does, because they are hot.

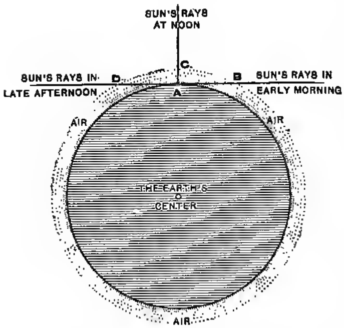


FIG. 425. — At sunset and sunrise the sun's rays pass through the dust-filled air for the distances DA and BA in contrast with the small distance CA at noon.

Mirage. — Among the changes in light as it is refracted and reflected in its passage through the atmosphere, is the phenomenon of *mirage*. This is caused by refraction and reflection when layers of air have different temperatures and consequently different densities. In deserts and on the sea, mirage and a related phenomenon called *looming* are especially perfect, but it commonly shows objects inverted, — for example, a vessel with the masts downward. The phenomenon of mirage is especially deceptive in deserts, where, owing to the reflection of the blue of the sky, it sometimes gives the appearance of water and often leads travellers astray.

Halos. — The drops of water in the rainbow cause refraction and reflection of the light which is passing through the raindrops. Similar changes in the light rays sometimes cause *halos* around the sun or moon, due to the refraction of the light which passes through the icy crystals of thin clouds high in the air.

Colours due to Reflection and Absorption. — Reflection also causes colours of leaves, flowers, and other objects. For example, when light reaches white paper, all the waves are reflected and the paper appears white, but when light reaches black cloth, most of the rays are *absorbed* and very little light is reflected. Still other objects absorb some of the waves and reflect others, thus giving colour, as in a red flower which reflects an excess of red waves, or green leaves, which reflect an excess of green waves.

SUPPLY OF WARMTH TO THE ATMOSPHERE

Radiant Energy. — The fire in a stove causes the iron of the stove to be warm, so that we feel its warmth at a distance of several feet. This is because waves of heat from the stove have passed that distance through the air. When the top of the stove is very hot, the iron becomes red because the waves produce, not only heat, but the sensation of light as well. This form of energy which we call heat and light is known as *radiant energy*, and the process of emitting it is called *radiation.* The sun is a great centre of radiant energy, but some of the stars may be even larger and hotter, although they do not influence the earth on account of being much farther away from it. The radiant energy from the sun which reaches the earth is called *insolation.*

Radiation causes the loss of heat and bodies become cooler, as in the case of a stove which will radiate all its heat and become cold in a few hours after the fire is out. Although the sun has been radiating its heat outward in all directions for millions of years, a very long time will be required for it to radiate all of its heat and become cold. Only a small proportion of the heat radiated outward by the sun is intercepted by the earth (Fig. 426), but this radiant energy has fundamentally important effects upon the earth's surface.

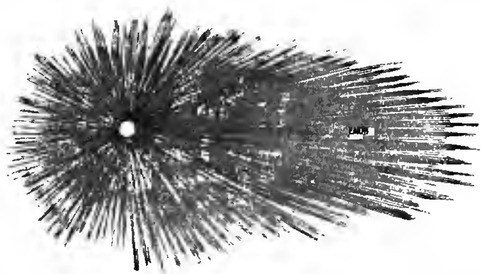


Fig. 426. — The earth and the sun's rays, showing how small a portion are intercepted by this small planet.

Transparent and Diathermanous Substances. — Air, glass, and certain other substances allow light to pass so freely that they are called *transparent.* They also allow heat to pass freely and are, therefore, called *diathermanous.* Because the atmosphere is diathermanous, the sun's rays reach the earth's surface at midday with comparatively little loss. Dust particles interfere with the passage of the rays of heat as well as light, in the latter case causing the brilliant colours at sunrise and sunset, and, in the former, the cooler atmosphere when the sun is low and passes through a great thickness of dust-laden air near the horizon. Late in the afternoon, for example, we may actually look at the setting sun, because many of the rays are intercepted by the particles of dust. Quite as important as the presence of dust, however, is (*a*) the greater thickness of air traversed by the sun's rays (Fig. 425) and (*b*) the angle of insolation (Fig. 427), the rays spreading over a broader surface than at midday and, therefore, heating it less. Water vapour is also very important in absorbing sunlight.

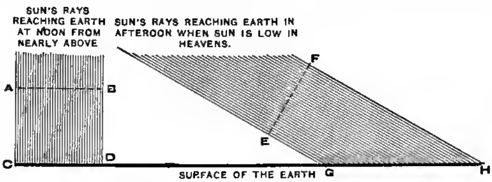


Fig. 427. — The cross-sections of sun's rays AB and EF are equal, but at noon they are concentrated on the width of ground CD, while at sunset they are spread over the greater width GH.

Heat from Direct Passage of Radiant Energy. — Very little heat is absorbed by the atmosphere during the direct passage of radiant energy through it. This is demonstrated by the fact that, instead of being much warmer on the tops of high mountains, which are nearer the sun than the plains at their base, the atmosphere is usually cooler there. As a matter of fact, light and heat rays pass through the atmosphere without heating it, except as these rays are interfered with by particles of dust and drops of water, which cause the absorption of heat rays. Consequently, the earth's surface would be cold if it depended for its heat upon the warming of the adjacent atmosphere as the radiant energy passes through it. The ether of space is exceedingly cold because there is no dust or water vapour there to interfere with the passage of radiant energy through space. The heat which reaches the earth's surface, however, supplies warmth to the atmosphere by indirect means.

Heat by Reflection and Absorption. — Water not only reflects light, but it also reflects a large percentage of the heat rays which reach its surface. This is the reason we often become sunburned when we are out in a boat. The streets of a city or the stone walls of a quarry are warmer than the open country, because the sun's rays are reflected from the pavements and walls and rocks. Some bodies, however, reflect little heat, and the sun's rays are mainly used in warming them directly. Such bodies are said to absorb heat. This is especially true of black objects, and because white cloth reflects heat and black cloth absorbs it, it is cooler to wear white clothing than black or blue in the summer. Accordingly, the uniforms of United States navy officers, who are in service in the tropics, are made of white material; and men go without their coats in summer in the temperate zones because, entirely aside from the weight of the coat, the reflecting white clothing is, in most cases, cooler than the absorbing black clothing. This can be readily proved in winter by placing two pieces of cloth, one black, the other white, on a snow bank in the sun. The black cloth soon sinks into the snow, because the sun warms it, but the white cloth remains on the surface, because it reflects the heat rays and is not warmed.

Heat by Radiation. — A coil of iron pipes containing steam or hot water is warmer than the air surrounding it in a room, and, therefore, radiates its heat out into the room and is known as a *radiator*. The earth radiates into space the heat that comes to it from the sun. Indeed, the earth would otherwise become warmer and warmer, instead of maintaining a fairly constant temperature. During the day more heat is absorbed than can be radiated, but at night radiation cools the ground. In summer when the days are longer than the nights, the ground grows warmer, and in winter when the opposite condition is true, radiation so far exceeds the supply of heat that the ground becomes cold.

The rocks and soil of the earth radiate heat and hence cool more quickly than water. They are said to be better radiators, and they are also more effective absorbers of heat than water is. Accordingly, in winter the land becomes cooler than the sea, and on frosty nights those objects which radiate their heat most rapidly generally have the most frost.

Heat by Conduction. — When a flatiron is placed on a stove, the handle of the flatiron very soon becomes so hot that it is unpleasant to pick it up. This heat has been *conducted* to the handle from the bottom of the flatiron, which is the only part in contact with the hot stove. In a similar way some of the sun's heat is conducted below the surface of the ground or water, and some of it into the air that rests upon them. Water, air, and ground, however, are not as good conductors as iron, and ground is so poor a conductor that below a depth of from 30 to 40 feet there is practically no difference in temperature from summer to winter.

Heat by Convection. — The lower layers of water in a kettle are heated by conduction, since they are directly in contact with the hot metal. Cool water is heavier than warmer water, and the cool upper layers of water in the kettle, therefore, tend to sink and displace the warm lower layers, which are crowded up by the settling of the cooler layers from above. This is *convection.* If the water continues to warm, it will finally boil, but not until all of the water in the kettle has been heated by conduction and moved away by convection so that the cooler water may take its place. Similar convection takes place in a lake in the autumn, with the opposite result. The surface layers of water are gradually cooled in the autumn by radiation. These cool layers settle, and the warmer lower layers of water rise to the surface and are there cooled by radiation and then settle to the bottom to give place to the warmer water. Until all of the water in the lake has been cooled by radiation so that it has approximately the same temperature, it is impossible for the lake to freeze. It is for this reason that shallow ponds and bays of slight depth freeze before deep lakes are covered by ice. This also is convection.

Similar convection occurs in the air. Near a lamp, for example, the air is warmed and becomes lighter and is pushed out of place by the settling of the heavier surrounding air. This movement of heavier air crowds up warm air in the vicinity of a lamp or stove, and causes a draft in a fire. The crowding upward of the warm air causes an upward movement in the chimney.

Heat from the sun is the cause of extensive convection upon all parts of the earth. The air is warmed in one place by radiation and conduction of heat from the ground, or water, and is pushed out of place by the settling of the heavier cool air drawn down by gravity. In this way the air is set in motion and we have wind. When air rises its temperature may decrease notably without appreciable loss of heat through conduction or radiation, but wholly through expansion. This is *adiabatic* cooling. With compression of descending air a corresponding heating occurs.

Measurement of Temperature

Thermometers. — The measurement of temperature of the air is made with the *thermometer*. The commonest type of thermometer is a hollow, sealed glass stem or tube, of small calibre, with a bulb containing mercury at the bottom. The air in the tube has been removed before the tube is sealed, and the mercury is, therefore, free to rise and fall in the vacuum of the tube. In the thermometer we take advantage of the principle that mercury or alcohol expands and requires more space when warmed, and contracts and takes up less space when cooled. It would be possible to use many different liquids in the thermometer, but mercury or alcohol is commonly used, chiefly because it does not freeze at ordinary temperatures. Mercury is ordinarily used in the thermometers which are not to be exposed to cold greater than the temperature of about $-40°$ F., the freezing point of mercury. Alcohol or other fluids, such as certain light oils, are used for thermometers which are to be exposed to lower temperatures.

With the change of temperature, the mercury in the bulb expands or contracts and thus causes a tiny thread of mercury to rise and fall in the tube. The measurement of the temperature by the rise and fall of the liquid in the tube makes it necessary to have the tube graduated in degrees.

Fahrenheit and Centigrade Scales. — There are several methods of division of thermometer tubes, the one most commonly used in America and England being the *Fahrenheit* scale (F. or Fahr.). In the Fahrenheit scale the boiling point of water is placed at 212° and its freezing point at 32°. A more simple scale of graduation is known as the *Centigrade* (C. or Cent.), which is most commonly used on the continent of Europe. In this, the freezing point is placed at 0°, and the boiling point at 100°. To convert Centigrade to Fahrenheit at temperatures above freezing, multiply by 1.8° and add 32°. For example, 10° Cent. = 50° Fahr. ($10° \times 1.8° = 18° + 32° = 50°$). The Fahrenheit scale was perfected about 1714 by Fahrenheit, and the Centigrade scale 28 years later by Celsius and Linnæus. Various other scales have been proposed. The *Rêaumur* scale is based upon a freezing temperature at 0° and the boiling temperature at 80°, while the inverted scale of *Celsius* probably had 0° for the boiling point and 100° for the freezing point. The latter is obsolete, and the Réaumur is used only in Russia and parts of Germany.

Metal Thermometers and Thermographs. — There are also *metal thermometers*, based upon the same principle of contraction and expansion with changes of temperature. Thermometers of this kind, made of metal strips connected with a hand that moves over a graduated dial, are often to be seen in front of city stores.

Metal thermometers are also used in connection with self-recording temperature records. They have an arm bearing a pen which is moved as the temperature changes. The pen is placed so that it presses against a piece of paper on a cylinder which is revolved by clock work. With the daily and seasonal variations of temperature the pen rises and falls, while the paper on the cylinder revolves regularly, so that the pen draws a line recording the temperature continuously. These self-recording thermometers are called *thermographs*.

Maximum and Minimum Thermometers. — Another type of thermometer is used for observing the extremes of heat and cold at times when the observer is away from his instruments or at places to which he is unable to go, as in the case of thermometers sent up in balloons or lowered beneath the sea with sounding apparatus. The *maximum thermometer* has a constriction in the tube just above the bulb. The thermometer rests horizontally rather than vertically. When the temperature rises, the expanded mercury will be pushed up through this constriction, but when the temperature falls there is no such force to push the mercury back through this constriction and the thermometer, therefore, records the maximum temperature which has been reached. Later the mercury is sent back into the bulb by whirling the thermometer rapidly about a pin provided for that purpose.

In the *minimum thermometer* alcohol is used rather than mercury, and the tube contains a small piece of coloured glass known as the index. The surface tension at the top of the column of alcohol keeps the index in position and pulls it down when the temperature falls. When the temperature rises, the alcohol flows freely around the index, and, therefore, when the temperature increases and the alcohol flows back, the index remains in the lowest position which it has reached. Accordingly the position of the top of the index indicates the lowest temperature which has occurred since the minimum thermometer was set. After making an observation the minimum thermometer is set again by lifting the bulb until the index slides back to the terminus of the alcohol column.

Instrument Shelters. — In keeping accurate meteorological records it is necessary to take care to place the instruments where they are not influenced by local conditions. Thermometers, for example, give very different readings, depending upon whether they are in the shade or in the sun. The usual method is to use an instrument shelter with the sides made of slats, so that the air will circulate freely and the sun and rain will not reach the thermometer. It should be placed either on open ground or on a roof.

Warming of the Land

Effect of Absorption and Radiation. — During the day, the sun's heat causes the land to be warmed by absorption. The heat absorbed at the surface is conducted a few feet into the ground, although generally not much farther than the roots of plants reach. It is thought that the reason the ground nowhere becomes excessively warm by absorption is because so much of the heat is lost by reflection, by radiation, and by conduction to the air. Everywhere, however, the ground is warmed during the heat of a sunny day and may be far over 100° F. It is then cooled off at night by radiation, especially if the sky be clear.

In the tropical region, during the long hot days, radiation is unable to remove all the heat that is absorbed, and the ground does not become very cool at night, except in places like the trade wind deserts, where water sometimes freezes at night. In the temperate zones the absorbed heat probably accumulates during the summer when radiation does not remove it all, but in winter the radiation during long nights removes so much of the heat from the earth that the ground freezes. In the polar regions the radiation during the long winter is so extensive that it causes the ground to freeze to depths of hundreds of feet, and the short cool summer results in the absorption of so little heat that the frost goes out of only the upper layers of the ground. In central Alaska near Fairbanks, for example, the frost extends to a depth of more than 175 feet and is present in summer and winter, while in the northern United States the frost in winter rarely extends more than 4 or 5 feet into the ground, and is entirely removed during the summer.

There are still other reasons for minor local differences in the warming of the lands. Dark-coloured surfaces absorb more heat and are, therefore, warmed more quickly than light-coloured soil and rocks. Bare earth is warmed more quickly than that covered by plants. Sunny, south-facing slopes will absorb more heat than shady, north slopes. Valley sides reflect heat and interfere with radiation from the valleys and with winds. They are, therefore, warmer than the adjacent hilltops.

Warming of the Water

Reasons for Warming more Slowly than Land. — The reason that water warms less rapidly than the land is, first, because of reflection. The surface of the water, especially when calm, reflects more heat under bright sunshine than the land, so that there is less heat left to warm the water. Moreover, because of its circulation the movable water is set in motion when one part of it is warmed, so that the heat is distributed in a way that is impossible in the motionless land. Transparency of water also results in the transmission of heat below the surface. So some heat goes to warm the deeper layers, while in the land all of the heat which is absorbed is used to warm the upper layers which, therefore, become much warmer than the upper layers of water. Sunlight penetrates dimly to depths of several hundred feet in the water, and, although the water is not warmed appreciably at this depth, the opaque land, into which the sunlight cannot penetrate, is never warmed to a depth of more than a few feet by the absorption of heat. Further, much of the heat is expended in evaporating the water. This is called *latent heat* or *heat of vaporization*. Lastly, it requires twice as much heat to raise the temperature of water 1° as it does to raise the temperature of land an equal amount.

Reasons for Cooling more Slowly than Land. — On these accounts even the small bodies of water, such as ponds and lakes, warm more slowly during the day and during the summer than the adjacent land. They likewise radiate their heat more slowly at night and in winter than the adjacent land, because water is such a poor radiator that it cools more slowly than soil and rock. There is, therefore, a smaller range of temperature from day to night and from summer to winter in large bodies of water, and the climate over them and at their borders is characterized by less extremes of heat and cold than the climate over the land.

Warming of the Air

Effect of Radiation, Conduction, and Convection. — As already indicated (p. 717), some of the sun's rays are intercepted in their passage through the atmosphere from the sun, and some of the heat rays radiated from the earth are, likewise, intercepted by the dust in the air. The air is, therefore, not perfectly diathermanous. In addition to this direct heating of the air by the passage of radiant energy is the warming by conduction from the ground to the lower layers of the atmosphere. Radiation is even more effective in warming the air than conduction, which acts slowly, over short distances. These warmed lower layers of air are lighter and are, therefore, displaced by the settling of cooler, heavier, upper layers, so that the higher portions of the atmosphere are heated chiefly by convection.

Thus the atmosphere is seen to be warmed by radiation, by conduction, and by convection, just as the stove warms the air in a room in these three ways. At night and in winter the air is cooled by radiation and also cooled by contact with the ground. Radiation is interfered with by vapour and dust in the air, so that more heat is retained in the lower atmosphere on hazy and muggy days than in clear, dry weather. It is partly because of the fact that radiation fails to cool the ground that a hot, damp day may be followed by an oppressively warm night. Most of our unpleasantly warm summer weather comes in connection with just this sort of interference with radiation.

Distribution of Temperature over the Earth

Isotherms. — The distribution of temperatures upon the earth's surface is usually represented by lines known as *isotherms*. An isotherm may be defined as a line connecting places which have the same temperature. An *isothermal chart* is a map showing the temperature of a given area such as a state, the United States, or the world, for a given period or for a moment of time. Isothermal charts may be drawn to represent mean temperatures for the year or for a part of the year, or for a moment of time. For example, an isothermal chart of the world for January (Fig. 428) has isotherms passing through all places whose average temperature for the month of January is the same, and it will differ decidedly from an isothermal chart for the year, where

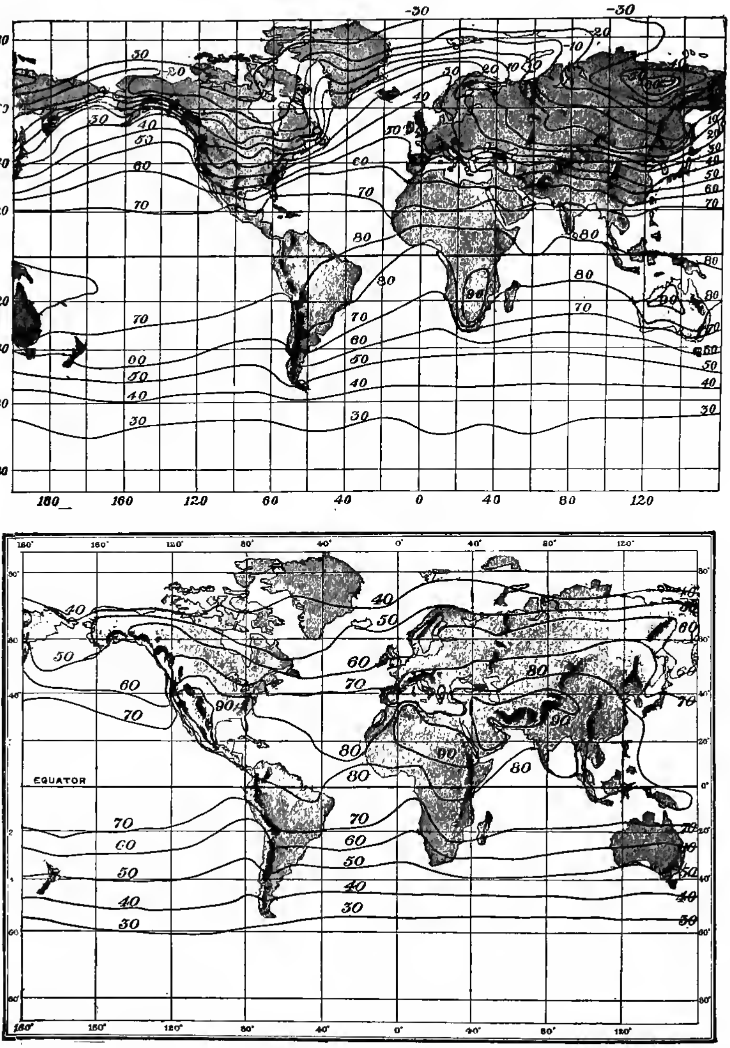


FIG. 428. — Isothermal charts of the world for January (upper map) and July (lower map).

the lines pass through places having the same average annual temperature.

The Zones. — The distribution of temperature from place to place on the surface of the earth is not simply a matter of heating of the land and water as a result of absorption, conduction, convection, and radiation, but also has to do with the distribution of heat in relation to (*a*) winds, (*b*) ocean currents, (*c*) position of the sun (Fig. 429), and (*d*) altitude. If the earth were heated by the sun's rays with relation to its spherical form, but with none of the four complications listed above, we should have three simple results: (1) all places between the equator and the tropics would be warmest, because they would receive the vertical rays of the sun; (2) all places between the tropics and the Arctic and Antarctic circles would be intermediate in warmth, because they would receive the rays of the sun at some time during each

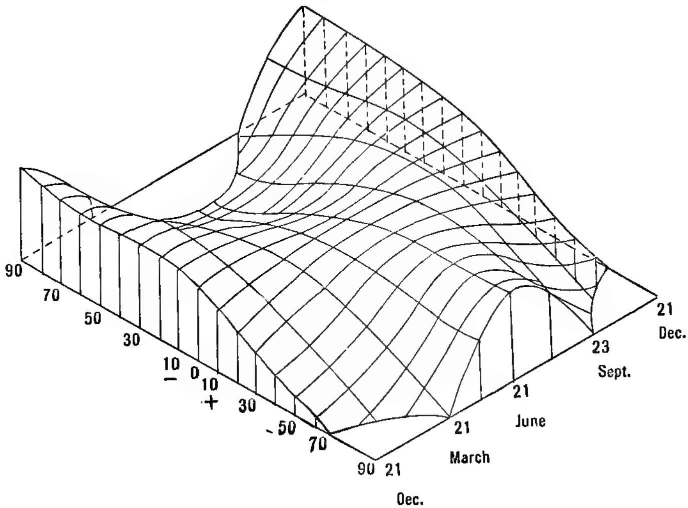


FIG. 429. — Davis's diagram to show the variation in insolation with latitude and with the season.

day in the year, while (3) the regions between the poles and the Arctic and Antarctic circles would be coldest, because the poles would have six months of sunlight and six months of darkness, while the areas within $23\frac{1}{2}°$ of the poles would have a variable number of days during the year in which the sun's rays did not reach the earth's surface at all.

It is usual in grammar school geography to have a map of the zones with one equatorial or torrid, two temperate, and two polar or frigid zones (Fig. 481). The boundaries between these zones are the Arctic and Antarctic Circles, and the Tropics of Cancer and Capricorn. The actual temperature within these zones, as we may now study it in college geography, differs very much because of the distribution of heat in accordance with the four features listed above.

Effect of Winds. — The effect of distribution of heat by winds is to carry the temperature of warm lands to the cooler ocean in some places where the wind blows from the land to the sea, and to carry the temperature of the temperate zone into the polar region, or *vice versa*. A city on the sea coast, for example, might have a lower temperature than a city some distance inland, if the wind were from the ocean in summer at a time when the sea was cooler than the land. The lower temperature of the coastal city would then be due to the influence of the wind in carrying the temperature of the cool ocean inland to the warm land. The opposite might be true at another season. At times, when a breeze is blowing from the warm land to the cooler sea, the temperature upon a vessel at anchor in a harbour is warmer than would be the case if there were a calm, because the higher temperature of the land is being carried out upon the water. Likewise in the temperate zone of the northern hemisphere, a north wind is likely to be cool, or even very cold in winter, because it carries southward the temperature of the land at a latitude which is cooler because it receives the sun's rays at a lower angle and because the nights are longer.

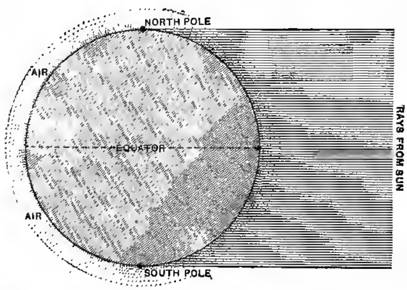


FIG. 430. — The sun's rays always reach the poles at an angle, therefore passing through a greater thickness of air, slanting over a broader area, and heating the earth's surface less than in the temperate and tropical regions.

Effect of Ocean Currents. — The ocean currents also distribute the temperature from place to place; for example, Iceland, which is on the Arctic Circle, has a temperature similar to that of New England and Newfoundland because the warmer water of the temperate zone is carried northward to the latitude of the Arctic Circle. In a similar way a cold ocean current from Greenland and Labrador bathes the coast of the Maritime Provinces of eastern Canada and gives it a lower temperature than it would receive from the direct heat of the sun

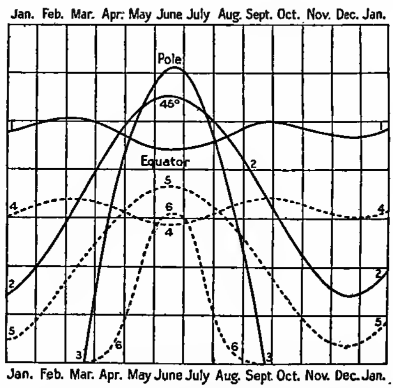


FIG. 431. — The annual variation in insolation at the upper limit of the atmosphere with latitude (solid lines), 1 at the equator, 2 at latitude 45°, 3 at the north pole. Curves 4, 5, and 6 (dotted lines) show the value of insolation at the earth's surface, in the same three regions, after passage of the heat through the atmosphere. (Angot.)

in this latitude. The cold current from the Antarctic Ocean has a similar effect upon the coast of Chile in South America.

Effect of Position of the Sun. — The heating power of the sun is greater when it is high in the heavens at noon than in early morning or late afternoon. It is less in winter than in summer and less in the temperate than in the tropical zones. The reason why the sun's heating power is less when it is low in the heavens is because (1) the heat rays pass through a greater thickness of dust-laden air when the

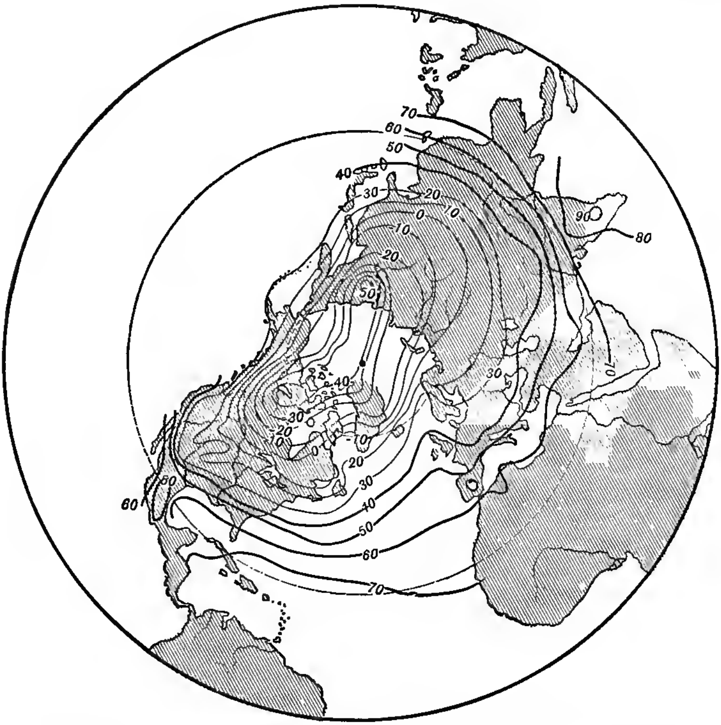


FIG. 432. — Isotherms in the north polar region for February, 1878–1887.

sun is low (Figs. 427 and 430), and (2) fewer rays reach and heat a given surface. Accordingly, we have three results of variable positions of the sun: (1) the amount of heat given by the sun's rays varies each day as the angle at which the sun's rays pass through the air is changed; (2) the seasons of summer and winter occur in both hemispheres as the sun is first high and then low in the heavens; (3) the climate is hottest in the tropical zone, where the sun is vertical at some point every day in the year, and is cooler between the tropics and the Arctic and Antarctic circles, where the sun's rays are never vertical and are inclined at lower and lower angles as the North and South poles are approached (Figs. 429, 431, 432).

Effect of Altitude. — There is an average decrease in temperature at the rate of about 1° F. for every 300 feet of ascent, as we know from observations upon high plateaus and mountains and the records of thermometers which have been carried up in balloons. This is because there is less warm ground to radiate heat into the upper layers of the atmosphere, and the warm air, which carries some heat to the upper layers by convection, expands and cools as it rises. It therefore supplies less and less heat as the altitude increases. Accordingly, at the equator a mountain 15,000 feet, or three miles high, has a frigid climate because of the coolness of the upper air and in spite of the fact that the sun's rays are never very far from the vertical. The smaller conduction to the air from the limited summit area of a mountain top also results in less heating of the air near mountains. It is also a matter of common observation that highlands are sometimes cooler than neighbouring plains. The fact of the cooling of expanding air may be observed by the use of a pump in inflating a bicycle or automobile tire, for the air pumped into the tire is compressed, or made more dense, and is, therefore, warmed. If the cap is taken off the tire, and the finger held in the air which rushes out, it may be noted that this air is cooler. Its coolness is due to the fact that it expands as it escapes.

In spite of the fact that cool air surrounds the tops of mountains and high plateaus, they may become quite warm at noon and in the early afternoon as a result of exposure to the direct rays of the sun. Persons ascending mountains often observe that they are very warm, if sitting in a protected sunny place, but if they sit down only a few feet away in a shady spot or where the wind is blowing, they feel very cold. As soon as the sun ceases to shine, however, radiation goes on so rapidly in the clear, thin, upper layers of the air, that even the warm places quickly cool off. The temperature on a highland may be as much as 90° at midday and as low as 10° at night. This is the basis of the fact that some of the people dwelling upon the plateau of Mexico habitually wear a blanket, the *sarape*, because the altitude of the plateau is such that if the sun goes behind a cloud the air is so cool that it is necessary to wrap the sarape around the head or throat to avoid catching cold.

The Stratosphere or Isothermal Layer. — The decrease in temperature with increase in altitude was formerly thought to continue upward more or less indefinitely. About 1901, however, it was discovered that at an altitude of over 6 miles in the north temperate zone the temperature of the atmosphere becomes stationary and even increases slightly. This warmer portion of the upper air (Fig. 433) is called the *stratosphere*, but the name *isothermal layer* has also been applied to it. Its upper limit is unknown. Its lower limit increases in altitude toward the equator, at least in the northern hemisphere. It may be as low as 23,000 feet in the Arctic region, 35,000 to 40,000 feet in England and central Europe, 43,000 feet near St. Louis in United States, and something in excess of 50,000 feet over the Atlantic Ocean

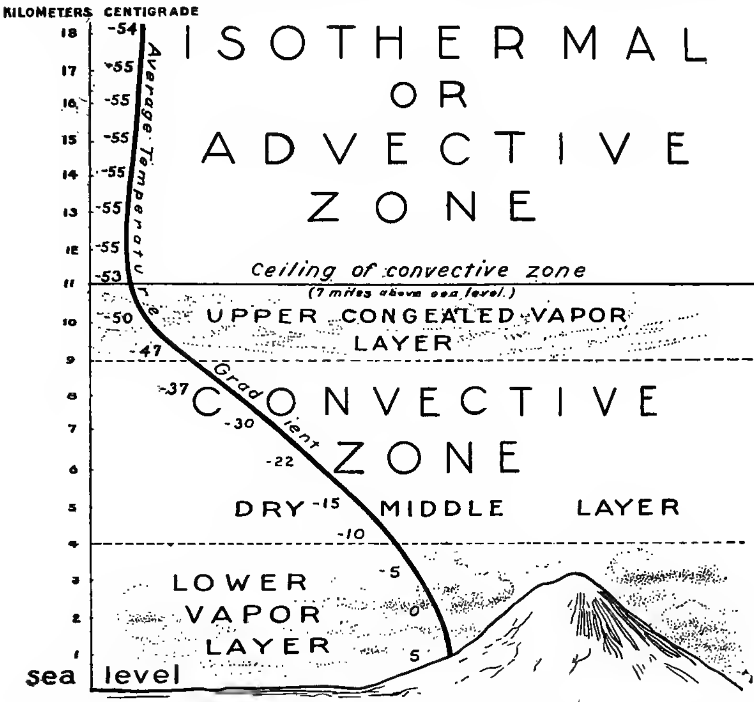


FIG. 433.—The temperature gradient near the earth's surface and in the isothermal layer, from explorations with sounding balloons and kites. (Hobbs.)

in the tropics. Its average summer temperature (−60° F.) is warmer than the winter temperature (−71° F.). Its cause is not yet well understood.

Within this upper portion of the atmosphere convection does not go on freely as in the lower air. Practically all the clouds are within the convective zone.

Other Causes for Variations in Temperature. — There are minor influences upon the distribution of temperature: for example, (*a*) according to the situation, as in the case of exposure to the wind, (*b*) in accordance with the nature of the rock, which results in greater heating of dark-coloured rock, and (*c*) as a result of the influence of water bodies.

Daily and Seasonal Temperature Changes

The Normal Daily Range. — As may be seen from Fig. 434, the warmest part of the day is not at noon when the sun is highest in the heavens, but at about 3 o'clock in the afternoon. This is because the heating of the ground in the morning was delayed because of the necessity of warming what had been cooled off by radiation the night before. After the ground is warmed there is a continued rise in temperature until the sun is so low in the heavens that radiation goes on at a rapid enough rate to exceed the heating of the ground. Accordingly, the ground and air commence to cool two or three hours after the sun's rays are vertical, and continue to do so until sunrise. This results in the coldest period being just before sunrise rather than at midnight.

A number of conditions frequently interfere with the normal daily range, as, for example, a cloudy sky, which prevents the temperature from rising because the clouds interfere with the passage of the sun's rays, or the blowing of a cold or warm wind, which may cause the temperature to fall during the noon hours, or to rise during the night (Fig. 500).

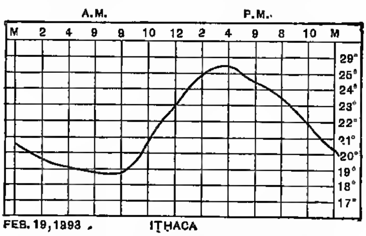


Fig. 434. — The normal daily range of temperature in eastern United States.

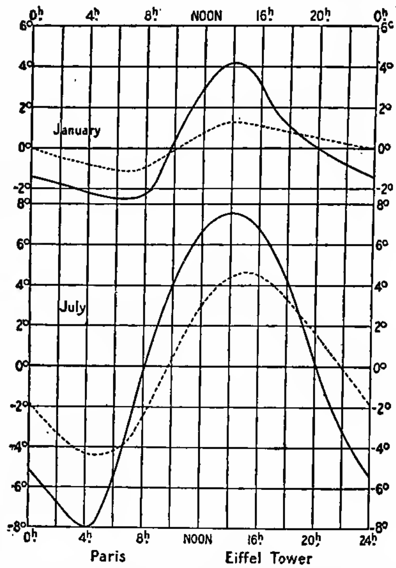


Fig. 435. — Daily range of temperature in winter and in summer, at Paris (solid line) and Eiffel Tower (dotted line), showing the influence of altitude. (Angot.)

The amount of temperature change from day to day differs from time to time and from place to place. Thus when cool nights follow warm days, the range exceeds that when cool nights are followed by cool days. In winter, the daily range is generally smaller than in summer, in parts of the temperate zones it is less than at the equator, and at sea it is less than on the land. The normal curve of daily range of temperature is shown in Fig. 435. Figure 436, showing the change in temperature for six successive summer days, illustrates departures from the normal curve. Likewise, Fig. 437 illustrates the variation in daily range for selected stations from the Arctic region to the temperate zone and near the equator.

The Seasonal Range. — The normal curve of seasonal range is similar to the normal curve of daily range. A record of average

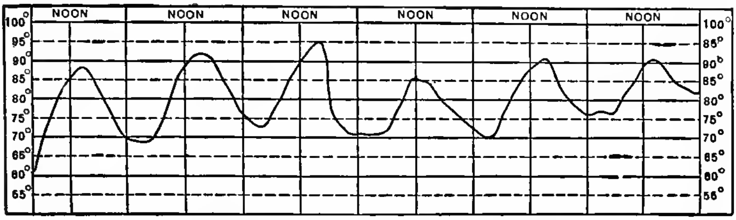


FIG. 436. — Record of the changes in temperature at Ithaca, N.Y., for six successive days.

temperature from day to day based on many years of observation shows that in the northern hemisphere there is a steady increase in temperature from January to July or August and a gradual decrease from July or August to January (Fig. 438). The middle of the summer is June 21, but, in the long run, the warmest month of the year is July, because, as in the case of the daily range, the ground radiates so much of its heat during the winter that it must be warmed before the temperature begins to rise, and the

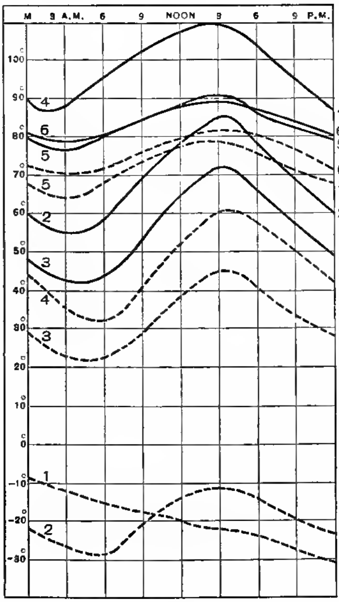


FIG. 437. — The daily range of temperature of the normal sort for winter (dashed lines) and summer (continuous lines). (1) Arctic; (2) St. Vincent, Minn.; (3) Djarling, India; (4) Jacobabad, India; (5) Key West, Fla.; (6) Galle, India; 5 and 6 are near the warm ocean.

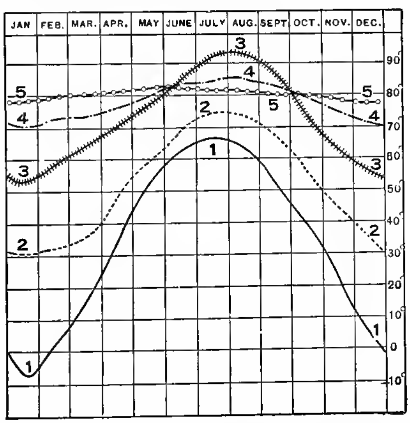


FIG. 438. — The seasonal range of temperature. (1) St. Vincent, Minn.; (2) New York State; (3) Yuma, Ariz.; (4) Key West, Fla.; (5) Galle, India. 4 and 5 are near the equable ocean.

winter is in December, but the coldest part of the winter is in January, somewhat as the coldest part of a day is later than midnight.

Figure 438 shows the curves of seasonal range in various parts of the world such as Minnesota, Arizona, New York, Florida, and India. It will be noted that the range of temperature in Minnesota is very much greater than in India. Although the December and January temperature at the equator is high in contrast with the low temperature in the north temperate zone, the seasonal range is less than in the higher latitudes. Moreover, India is a peninsula projecting far into the ocean, and the range of temperature over the equable ocean is far less than over the land. In the southern hemisphere the coldest part of the year is the summer of the northern hemisphere. There are similar differences in seasonal range of temperature as a result of altitude, deserts, and various other factors.

For references to literature on Light and Warmth in the Atmosphere, see pp. 744–745.

CHAPTER XXIV

RAIN AND OTHER FORMS OF WATER

Water Vapour and Humidity

The Source of Vapour. — The water vapour in the air is chiefly supplied by evaporation from the surface of the ocean, rivers, and lakes, and from damp surfaces. The water vapour is everywhere diffused through the air, and even desert regions like the Sahara have some water vapour, or humidity.

Absolute Humidity. — The actual amount of water vapour in the atmosphere is spoken of as the *absolute humidity;* and this refers to the amount of water vapour, expressed in grains per cubic foot of air. The term *absolute humidity* is also applied to the vapour pressure, expressed in inches or parts of inches of the mercury column. When air contains as much water vapour as it can possibly hold, the air is said to be *saturated.* A room 10 by 15 by 15 feet at a temperature of 70° F. contains about 2.6 pounds (avoirdupois) of water in the form of invisible water vapour, when the air is saturated. Two and six-tenths pounds, therefore, represents the absolute humidity of a room of that size.

Relative Humidity. — The term *relative humidity* is used to represent the proportion of water vapour in the air in relation to the maximum amount which the air can contain at a given temperature. This is measured, not in grains, but in percentages. The relative humidity of completely saturated air is 100 per cent. Absolutely dry air would have 0 per cent relative humidity, and air containing only half as much moisture as is possible would have a relative humidity of 50 per cent. It is always necessary to state in the definition of relative humidity that this represents the proportion of water vapour in the air *at a given temperature.* The room referred to above, which contains 2.6 pounds of water, when the air is saturated at a temperature of 70° F., could contain much less water at a temperature of 60° F.

Relation to Evaporation. — In deserts, where the relative humidity is likely to be small, the air is so dry that evaporation goes on rapidly. In the tropical forest, on the other hand, the relative humidity is great, there can be only a little evaporation and, therefore, surfaces are likely to remain damp. The same conditions apply to the temperate zones, as in the regions of moderate rainfall in United States and Europe. In summer this lack of evaporation affects our comfort, because some days are humid or muggy, and at such times the heat is oppressive.

We perspire easily and are very uncomfortable because little evaporation can take place from the surface of the body when the air is humid. Evaporation from the skin cools us because some of the heat needed to change the perspiration into water vapour comes from the surface of the body. On clear, dry days we feel more comfortable because evaporation from the skin removes the perspiration, the percentage of relative humidity being so low that the air can readily evaporate a great quantity of water vapour. It is because of this that the temperatures of 90° to 100° or more in Arizona are not accompanied by as uncomfortable conditions as we experience under equal temperatures in the Mississippi valley or near the Atlantic coast, where the relative humidity of the air is greater.

Measurement of Humidity and Evaporation

The Hygrometer. — Several types of instruments are used for determining the humidity of the air. Among these is the *hair hygrometer*. This consists of a bundle of hairs from which the oil has been extracted. The hairs absorb the water vapour in the air and change in length with the changes in amount of absorbed vapour. This property is frequently observed by people whose hair becomes straight in damp weather. The hair hygrometer has a hand on a graduated scale, moving in one direction if the humidity is high and in the other if it is low.

The Psychrometer, or Wet and Dry Bulb Thermometers. — Another instrument for the measurement of water vapour is the *sling psychrometer*. This consists of two thermometers attached to a wooden or metal back. One of the thermometers has a piece of wet cloth around the bulb. The sling psychrometer takes advantage of the principle (1) that evaporation is more rapid in dry than in humid air, (2) that evaporation lowers the temperature. The method of using the sling psychrometer is to whirl the thermometers around for a minute or two so that the thermometers may come into contact with a large body of air. If the air is saturated, there will be no evaporation from the wet muslin, and the two thermometers will read the same, indicating a relative humidity of 100 per cent. If, however, the air is dry, the wet bulb thermometer will register a slightly lower temperature. The relative humidity of the air can be calculated from tables which show all common differences in temperature between wet and dry bulb thermometers and the corresponding variations of water vapour. Such tables may be obtained from the United States Weather Bureau.

The Evaporating Pan. — The commonest method of determining the rate of evaporation is with an *evaporating pan*. This consists of a dish of water in which is placed a ruler, graduated in inches and tenths of inches. Since evaporation varies from day to day and from place to place, this device makes it possible to tell how much water in the form of vapour is taken from the evaporating pan in a given time. It is of course necessary to prevent the rain from falling into the pan, or to allow for the rainfall, and to keep the pan freely open to the air.

Precipitation of Moisture in the Air

Relation to Increased Temperature. — It was stated above that the absolute humidity of the air depends upon the temperature. If saturated air, with its 100 per cent relative humidity, is warmed, it ceases to be saturated, because its capacity for moisture is increased. Accordingly, its relative humidity falls, and increased evaporation may take place. The desert region of the Sahara shows this, for the winds there are blowing toward a warmer region and consequently their

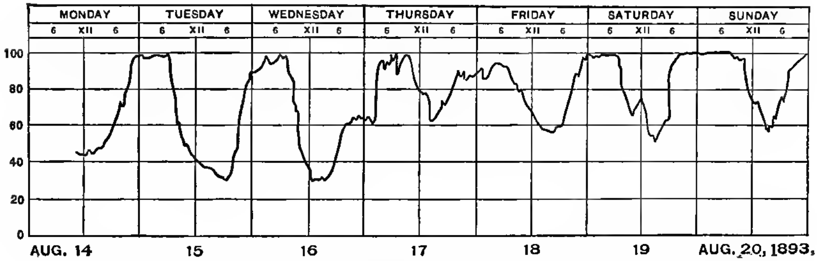


Fig. 439. — The changes in relative humidity with temperature, from a week's record at Ithaca, N.Y. The relative humidity is low, 30 to 60 per cent, at or soon after noon (XII); it is nearest 100 per cent at night when the air is cooled.

relative humidity is being lowered. This makes the air so dry that the ground is dried and a desert is produced.

Relation to Decreased Temperature. — The opposite condition is found where damp air is cooled so that its relative humidity increases to a point when the air becomes saturated. The amount of water vapour in a room with a temperature of 60° may represent a relative humidity of only 80 per cent. If, however, the air is cooled from 60° to 40°, the relative humidity of the room may increase to 100 per cent without the introduction of any more water vapour, because the capacity of the air for moisture is decreased by cooling. After the relative humidity reaches 100 per cent, and the air is saturated, any further cooling forces some of the water vapour to condense into liquid water, if the temperature is above freezing, or into snow or ice if the temperature is below freezing. This is known as *precipitation.*

Illustrations of Precipitation. — A person who wears glasses observes this phenomenon on cool days, for in walking out of doors the temperature of the glass of his spectacles is low, but the cool glass has no effect upon the cool air out of doors. As soon as he enters a warm building, however, the cool glass decreases the temperature of the warm air with which it comes in contact, and at the same time decreases its capacity for moisture. If the relative humidity of the warm building is 40 per cent, the air immediately in contact with the glasses may have its relative humidity increased to 100 per cent by cooling, and a little water vapour may be condensed, precipitated upon the glasses, causing them, as we say, to "steam." The same thing is shown by breathing against a cool window-pane. The breath is cooled to the point of saturation, and some of the vapour is condensed upon the glass of the window. Similarly, a glass of water "sweats" in warm, humid weather because the cool glass reduces the temperature of the air near it and raises its relative humidity to 100 per cent. As this is the point of saturation, some of the vapour must condense, forming drops of water on the outside of the glass. The point of saturation is often called *dew point* because dew is formed when this point is reached. Whenever air is chilled to the dew point, condensation takes place (Fig. 439).

Forms of Water

Formation of Dew. — When the ground is cooled by radiation, as it usually is at night, the lower layers of the air are chilled by contact with the cool ground. If the relative humidity of the air is fairly high, that is, if the air is damp, some of its water vapour will be condensed upon the ground as *dew*. It is rarely the case that the air is sufficiently humid so that dew forms before sunset. There are three conditions which check the formation of dew: first, exceedingly dry air; second, the movement of the air, so that the cool air is moved away before it reaches the dew point; and third, the checking of radiation by clouds.

The reason that dew forms so commonly on grass is that vegetation radiates its heat rapidly and, hence, cools early in the evening. A further factor, however, is the rise or transpiration of water from plants; there is sometimes also a slight supply of vapour from the ground. This water from the surface of leaves and grass and from the ground is removed during the day by evaporation, and it is only during the evening or night, when the cooling of the ground is sufficient to saturate the air, that evaporation is checked and small drops of water gather as dew on the surfaces of leaves and grass.

Formation of Frost. — It is a familiar observation that fantastic crystal forms often appear on a window-pane on cool nights in winter. This is commonly known as *frost*. Frost is formed upon leaves and plants and in general upon the earth's surface at low temperatures. Frost is a solid form of water which is made by the condensation of water vapour at temperatures below freezing. It is not always frozen dew, but may result from the direct freezing of water vapour at temperatures below 32° F. Usually it is a solid form of water vapour due to direct precipitation with the temperature below 32° F. Frost is also sometimes formed in favourable localities when the general temperature of a region is above freezing, and this is because either (*a*) the air is damper above low, swampy ground, or (*b*) cooled air settles down into the valleys, and frost forms there when there is none on the adjacent hills. Air also cools by radiation and conduction as it slowly descends the cool slopes.

The growing season for plants is commonly determined by the number of days between the last severe frost in the spring and the first severe frost in the fall. These are spoken of as *killing frosts*, because they stop the growth of plants or even kill them. Late spring frosts often do great damage to buds, and early frosts in autumn may destroy fruit that is not yet ripe. They are apt to come during nights when the air is so clear that radiation is exceedingly rapid. Sometimes in the spring plants are killed after having budded or leaved out, and, while

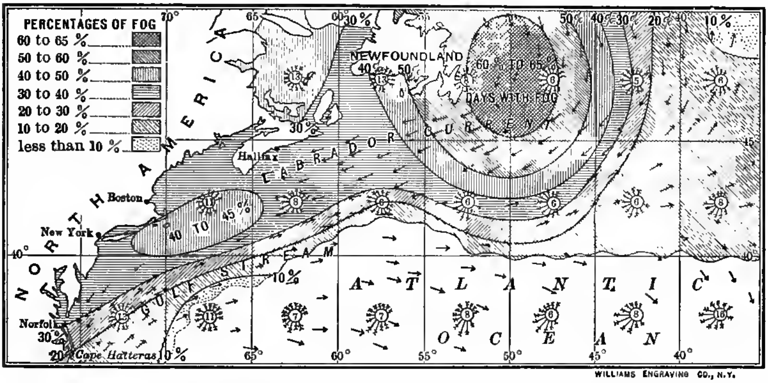


FIG. 440. — Map to show percentages of foggy weather on the Grand Banks of Newfoundland in June, 1913, in relation to the Labrador Current and Gulf Stream. Small arrows indicate ocean currents. Feathered arrows terminating in circles indicate winds: (*a*) the length of the shafts being proportional to the number of hours in 100 with wind in a given direction; (*b*) the number of feathers showing the force of the wind; and (*c*) the percentage of calms, light and variable winds being shown by the figure inside the circle. (From Meteorological Chart of the North Atlantic Ocean, U. S. Weather Bureau.)

they may recover after a light frost, a heavy frost usually results in there being nothing left to grow the next season except the seeds, bulbs, or roots.

A well-known phenomenon in connection with frosts in the autumn is the change in the colour of the leaves. The beautiful red and yellow colours of autumn foliage are due to frost. Later this kills the leaves and causes them to fall off most of the trees. During the cold winter season in the temperate zone, the trees and shrubs remain dormant and do not burst out into new life until, with the return of warmth in the spring, frosts are no longer common.

Formation of Fog. — If we breathe out into cool air, the breath becomes visible. What really takes place, however, is the condensation of the water vapour of the breath into tiny particles of liquid water of such minute size that they float and form a *fog*. Damp air is chilled in other ways besides being breathed out from the lungs, however. For example, fog is formed at night when the air over damp plains is chilled to the point of saturation. There is frequently fog because of the mixing of two currents of air, one of which is cool and the other warm and damp. This is the most common cause of sea fog.

Two places in the world which are famous for dense fogs are the Grand Banks of Newfoundland, and the vicinity of London. In the former locality (Fig. 440), on the path of trans-Atlantic steamers between the north of Europe and New York, the warm Gulf Stream and the cool Labrador Current are near together. The warm, damp air moving across the cool Labrador Current from the Gulf Stream is chilled so that its relative humidity is increased to 100 per cent and water vapour is condensed into particles of fog. The same thing occurs, though less commonly, when cool air from the Labrador Current moves into the region of warm air over the Gulf Stream. Consequently, this part of the ocean is nearly always foggy. Vessels going through this fog sometimes collide. Large ocean steamers are likely to run down the small fishing schooners which frequent the Grand Banks, fishing for the abundant cod and halibut and other fish there. Indeed, fog is one of the most dangerous features on the sea, in spite of the fact that cautious captains reduce their speed and blow fog horns to warn other vessels of their approach. Even then there is sometimes disaster, as in the wreck of the *Empress of Ireland*, during a fog on the lower St. Lawrence on May 29, 1914, when over 1000 people were drowned. Ships are also in danger of running aground in a fog. In entering harbours ships frequently have to stop and anchor because of the dense fog.

Another occurrence of dense fog is due to a different cause. In the vicinity of a large city, as in London, dust particles aid in the formation of fog by supplying solids upon which the water vapour may be condensed. It is thought that the large amount of dust, chiefly smoke particles, in the vicinity of London helps to produce the dense fogs there, though radiation would cause some fog near London, even if there were no smoke there. Fogginess has increased, however, with the growth of London and the increase in production of smoke. The fog is frequently so dense as to stop all traffic upon the streets, and not infrequently results in the closing of the stores in the city during the day.

Formation of Clouds. — Clouds are of much the same nature as fog, and, indeed, the lower clouds are fog. The higher clouds, however, caused by the condensation of vapour with a temperature far below 32° F. are composed of particles of snow and ice. During the summer many clouds are caused by the rise of damp, warm air to such altitudes that the air is cooled and the relative humidity increased to the dew point. The formation of clouds is chiefly due to the cooling which accompanied the expansion of the rising air. Another cause of cloud formation is the blowing of damp air over cold surfaces, such as the top of a mountain (Fig. 441). Another cause is the coming in contact of a warm and a cold current of air, one above the other; and clouds of this sort are common on days when the warm air is also very damp.

Types of Clouds. — The forms of clouds are varied, and, due to accidental relationships of air currents, they are sometimes fantastic, sometimes beautiful. The clouds which overspread the sky with an appearance of layers of strata are called *stratus* clouds. They are usually not very high above the earth, and often come so low as to lie upon the tops of the hills (Fig. 442).

On warm summer days the clouds formed by the rising and cooling of damp air assume a different shape and are called *cumulus* clouds. At an elevation of several thousand feet above the surface of the earth

Fig. 441. — Clouds in process of formation on the western slope of the St. Elias Range in Alaska and over the ice plateau of the Malaspina Glacier.

the vapour in the rising air begins to condense. Thus the cumulus clouds are apt to have a flat base. Above this may rise a series of domes and billows, sometimes a mile in height and often very beautiful, especially when lighted and coloured at sunset. On hot summer afternoons cumulus clouds often develop into what we call *thunder-heads*. They are then called cumulo-nimbus.

A type of cloud which forms still higher in the heavens is called the *cirrus* cloud. It differs from the other two types in being made up of transparent particles of ice, so thin that the sun shines through them. Rings around the sun or moon are often seen in cirrus clouds, which vary greatly, often having delicate feathery or plumed forms.

The gradations between these three types of clouds are given compound names, such as cirro-stratus, cirro-cumulus, or strato-cumulus. The rain cloud is called *nimbus*.

Precipitation of Rain. — The most important topic in connection with the discussion of the forms of water in the atmosphere is what

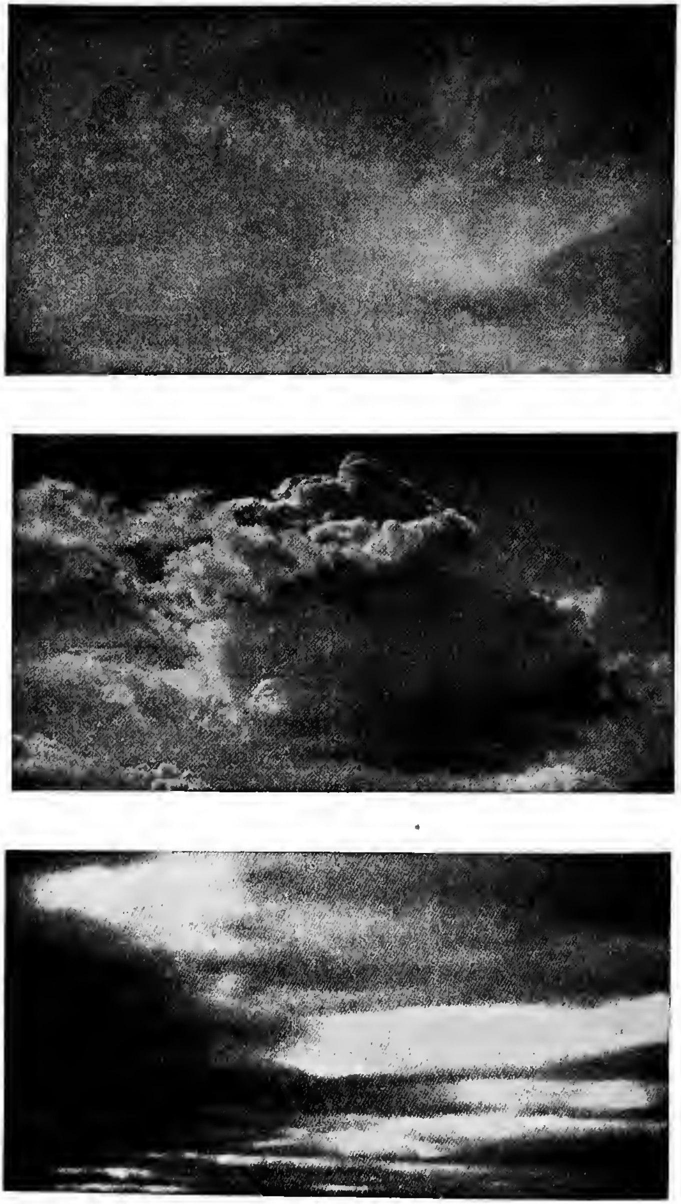


FIG. 442. — Types of clouds. Cirrus, above; cumulus, middle; stratus, below. (From Encyclopædia Britannica.)

makes it rain. This is, in general, a simple matter, following the explanation of the condensation of water vapour into dew, frost, fog, and clouds. The formation of fog, as already explained, is due to the condensation of water vapour as a result of the cooling of humid air until its relative humidity reaches the dew point. When fog particles are of small size, they float in the air in the fog or cloud; but they sometimes grow to such size that they fall as rain drops. The growth of rain drops to such size that they can no longer float in the air is due to (*a*) continued condensation of vapour, (*b*) the uniting of cloud particles. Rain, therefore, is only a continuation of the process of cloud or fog formation, but when water vapour condenses rapidly, as in thunder clouds in summer, the rain drops may assume great size.

It sometimes happens that there is cool, damp air at one level and warm, dry air at a lower level so that rain drops which are formed above may be evaporated on their way from the clouds and never reach the ground. Streamers of rain evaporated in this way are often seen in summer, descending part way to the earth.

Measurement of Rainfall. — The amount of rainfall is recorded by the *rain gauge*. Any cylindrical measurer, such as a pail with vertical sides, can be used to measure approximately the number of inches of water that fall on a given surface. The rainfall is usually so slight, however, that provision must be made to measure it accurately by collecting the water in a smaller space than the surface on which it falls, thus magnifying the depth of water.

The usual way of making a rain gauge is to have two cylinders one inside the other, the inner cylinder having a diameter of 2.53 inches, the outer one 8 inches. A funnel fits over the outside cylinder, and the opening at the bottom leads into the inside cylinder. The rain that falls in the funnel collects in the bottom of the inner cylinder to a depth of ten times that of the actual rainfall. By measuring this depth, the actual rainfall may be obtained. There are also *self-recording rain gauges*, the one most commonly used having a balanced pair of small receptacles so arranged that when the rain has filled one, this tips down and empties out the water, bringing the other receptacle in position to be filled. When this is filled, it likewise tips down and places the first receptacle in position, and an electrical connection records each time that the gauge is filled, so that the total rainfall is automatically registered.

The amount of precipitation for a region is commonly given as if it were all rain. Snow is melted, and then the depth of water is measured and considered as "rainfall." Instruments are sometimes used for measuring snowfall, but usually the snowfall is measured out of doors in some place where it has not drifted. It is usual to allow one inch of rainfall for every ten inches of snow.

Formation of Sleet. — Rain drops sometimes freeze on their way towards the earth's surface as they fall through a cold layer of air. This frozen rain is called *sleet*. Some sleet, however, is formed by the

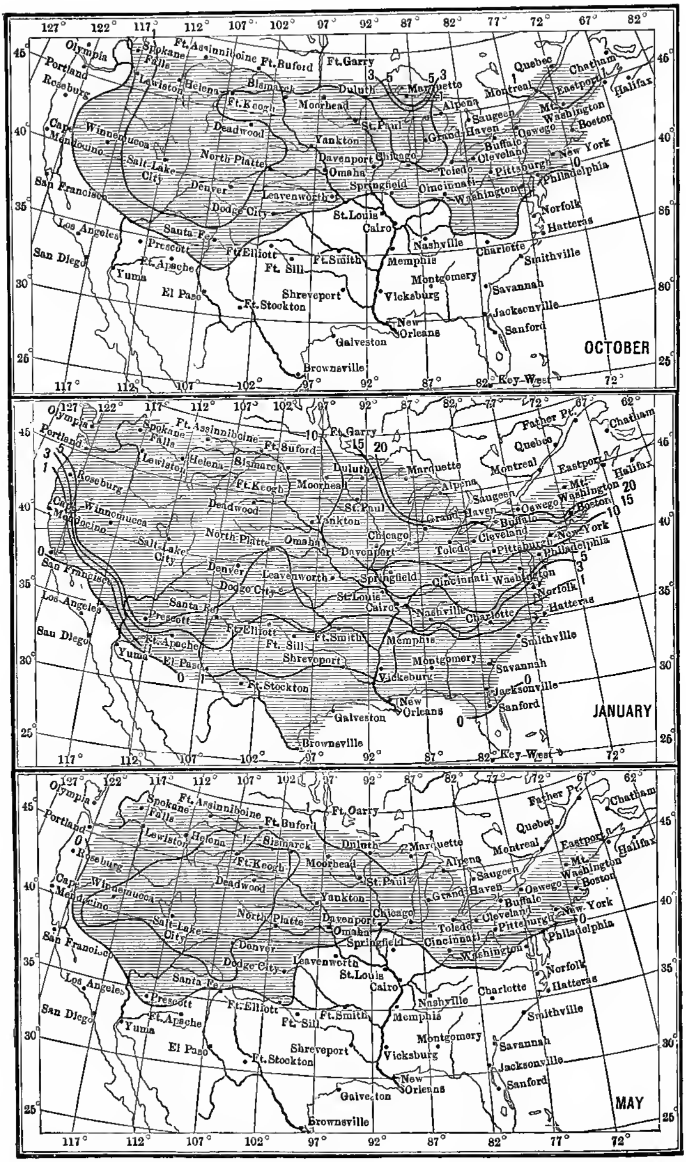


FIG. 443. — Snowfall map of the United States in late autumn, winter, and spring, showing variations with latitude, altitude, and the season. (U. S. Weather Bureau.)

partial melting of snow that is precipitated at higher levels, melted midway and then frozen before reaching the ground.

Formation of Snow. — Snowflakes bear somewhat the same relationship to rain that frost does to dew, being formed by the condensation of water vapour in a cloud at a temperature below the freezing point. Snowflakes are not frozen rain drops, as is the sleet, but are crystals, formed from water vapour without going through an intermediate liquid form. When snowflakes grow without interference, they form beautiful, regular crystals whose varied forms may be observed by allowing them to settle on the sleeve of the overcoat in winter, before they have had any tendency to melt on touching the ground. Snow crystals grow as regularly as salt and alum crystals in a slowly evaporating solution (Fig. 444). The feathery frost patterns on window-panes are also caused by a crystal growth when water vapour condenses at temperatures below 32°, but this is what we usually call frost and not snow.

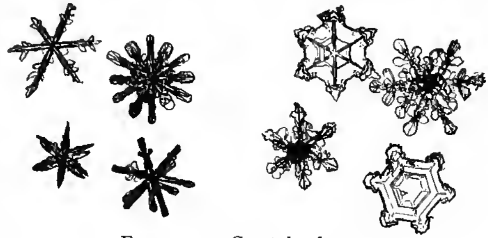


FIG. 444. — Crystals of snow.

Snowflakes are usually irregular because of one of several causes: (*a*) the crystals are often broken; (*b*) several crystals may unite by falling on one another, forming a matted mass, and most snowflakes are due to the formation of several snow crystals; (*c*) snow is sometimes partly melted in falling through a warm layer of air. It often happens that snow melts entirely before falling to the earth and reaches the ground as rain, as is often noticed in hilly or mountainous countries, where the hilltops are covered with snow, while only rain falls in the valleys a few hundred feet below.

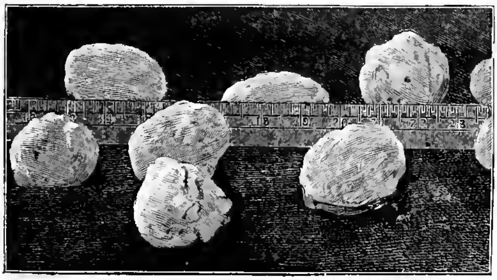


FIG. 445. — Hailstones. Figures on the scale are in inches.

Formation of Hail. — During severe thunder storms and violent tornadoes the air is whirled rapidly about in strong currents, and hailstones are likely to fall to the surface of the earth. They are sometimes as much as two inches in diameter (Fig. 445). If a hailstone is cut in two, it is seen to be a mass of snow and ice, usually more or less spherical and built up of several alternate layers of shells. This is because the hailstones are whirled up and down in the violent air currents, passing from cold to warm and back to cold currents of air. They often grow to considerable size, because they are kept suspended for a long time, and they may even rise in the air after falling part way to the earth. As soon as the air current ceases its rapid motion, however, the hailstones fall rapidly through the air because of their weight, and when they fall they often break window glass and do great damage to crops. Conditions favouring the formation of large hailstones are so uncommon that their destructive effects are limited to small areas and rare occasions.

References to Literature

Cleveland Abbe. The Aims and Methods of Meteorological Work, Vol. I, Maryland Weather Service, pp. 219–330; Treatise on Meteorological Apparatus and Methods, Annual Report of the Chief Signal Officer for 1887, Appendix 46, Washington, 1888, 392 pp.

Alfred Angot. Traité Élémentaire de Météorologie, Paris, 1899, 1907, 417 pp.

D. Archibald. The Story of the Atmosphere, London, 1901, 210 pp.

S. A. Arrhenius. Lehrbuch der Kosmischen Physik, Leipzig, 1903, pp. 473–925.

J. G. Bartholomew and A. J. Herbertson. Physical Atlas, Vol. 3, Meteorology, London, 1899.

F. H. Bigelow. Circulation of the Atmosphere of the Earth and Sun, Pop. Sci. Monthly, Vol. 76, 1910, pp. 437–461.

Alexander Buchan. A Handy Book of Meteorology, London, 1867, 204 pp.; Report on Atmospheric Circulation, Report on the Voyage of H. M. S. *Challenger*, London, 1889, 263 pp.

A. W. Clayden. Cloud Studies, London, 1905, 184 pp.

H. H. Clayton and S. P. Ferguson. Measurements of Cloud Heights and Velocities, Annals Astronomical Observatory Harvard College, Vol. 30, Part 3, 1892.

H. C. Cox and J. P. Goode. Lantern Slide Illustrations for the Teaching of Meteorology, Bull. 3, Geog. Soc. of Chicago, 1906.

W. M. Davis. Elementary Meteorology, Boston, 1894, 355 pp.

Henry Gannett. Rainfall Map of the United States, Pl. I, Water Supply Paper 234, U. S. Geol. Survey, 1909.

G. K. Gilbert. A New Method of Measuring Heights by Means of the Barometer, 2d Ann. Rept., U. S. Geol. Survey, 1882, pp. 403–566.

J. Hann. Lehrbuch der Meteorologie, Leipzig, 1901 and 1906.

A. J. Henry. Salton Sea and the Rainfall of the Southwest, Nat. Geog. Mag., Vol. 18, 1907, pp. 244–248.

A. J. Herbertson. Distribution of Rainfall over the Land, London, 1901, 70 pp.

A. J. Herbertson and E. G. R. Taylor. Oxford Wall Maps, 1909–1911: Rainfall Maps of the World, and of each continent separately; The World — Thermal Regions; The World — Pressure and Winds.

W. J. Humphreys. Origin of the Permanent Ocean Highs, Bull. Mt. Weather Observatory, Vol. 4, 1911, pp. 1–12; Vertical Temperature Gradients, *ibid.*, Vol. 2, 1909–1910, pp. 1–18, 183–192; Holes in the Air, Smithsonian Report for 1912, Publication 2198, Washington, 1913, pp. 257–298.

Mark Jefferson. Rainfall Map of the World, in an Atlas of Commercial Values, Boston, 1912, p. 62.

S P. Langley. Researches on Solar Heat and its Absorption by the Earth's Atmosphere, Bull. 15, U. S. Weather Bureau, Washington, 1884, 139 pp.

C. F. Marvin. Measurement of Precipitation, Circular E, Instrument Division, U. S. Weather Bureau, 1903; Barometers and the Measurement of Atmospheric Pressure, *ibid.*, Circular F; also Circulars A, G, and K.
W. I. Milham. Meteorology, New York, 1912, 541 pp.
J. W. Moore. Meteorology, London, 1894, 1910, 466 pp.
W. L. Moore. Descriptive Meteorology, New York, 1910.
A. Lawrence Rotch. Sounding the Ocean of Air, London, 1900, 184 pp.; Charts of the Atmosphere for Aeronauts and Aviators (with A. H. Palmer), New York, 1911, 96 pp.
Thomas Russell. Meteorology, New York, 1895, 277 pp.
Smithsonian Meteorological Tables. Smithsonian Misc. Collections, No. 1032, 1907.
J. Tyndall. The Forms of Water, New York, 1872.
U. S. Hydrographic Office. Illustrative Cloud Forms, Washington, 1897.
U. S. Signal Service. Professional Papers and Notes.
U. S. Weather Bureau. Daily Weather Maps; Rainfall and Snow of United States; Rainfall of United States; Snow and Ice Charts; Lettered Bulletins; Numbered Bulletins; and other publications.
Frank Waldo. Modern Meteorology, New York, 1893; Elementary Meteorology, New York, 1896.
R. de C. Ward. Practical Exercises in Elementary Meteorology, Boston, 1896, 199 pp.; Sensible Temperatures, Bull. Amer. Geog. Soc., Vol. 36, 1904, pp. 129–138; Relative Humidity in our Houses in Winter, Journ. Geog., Vol. 1, 1902, pp. 310–317.

PERIODICALS

Monthly Weather Review, Washington, D.C.
Bulletin Mount Weather Observatory, Washington, D.C.
American Meteorological Journal, Boston.
Quarterly Journal Royal Meteorological Society, London.
Symons' Meteorological Magazine, London.
Journal of the Scottish Meteorological Society, Edinburgh.
Die Meteorologische Zeitschrift, Brunswick.
Das Wetter, Berlin.
Ciel et Terre, Bruxelles.
Bulletin de la Société Belge d'Astronomie, Bruxelles.
Annuaire de la Société Météorologique de France, Paris.

CHAPTER XXV

WINDS

The Movement of Air

Relation between Winds and Air Pressure. — Wind is simply air in motion, usually in a horizontal direction. The cause of the wind is the pull of gravity upon air of different weights and the resulting displacement of lighter by heavier air. Wind may, therefore, be said to be due essentially to differences in the weight or pressure of different parts of the atmosphere. The atmosphere may be thought of as composed of a great many columns of air, held in place above the earth's surface by gravity. The column of air at one place, warmed by the sun's heat, is expanded, and becomes lighter than the columns of air near by which are not warmed and expanded so much. Accordingly the settling of the cooler, heavier air causes the rising of the expanded lighter air, just as it does around a lamp or in the neighbourhood of a fire. Heavy air, which is said to have high pressure, disturbs the equilibrium of light air, which is said to have low pressure. The heavy air moves or flows from places of high toward places of low pressure, forcing the light air to rise. In this way a circulation is set up which we know as the wind.

Barometric Gradients. — Since the variations in weight or pressure of the air are known as barometric pressure, the difference in air pressure which causes the wind is called the *barometric gradient*. This is so named because of the fact that the heavy air flows from a region of high pressure, or high barometer, to a region of low pressure, or low barometer, as if it were going down a gradient exactly as flowing water does. There is not a real slope or grade as in the case of a river, however, but merely lighter air in one place than in the other. Just as water flows rapidly down a steep grade in a river valley, so the air flows swiftly, or the wind has a high velocity, if the difference in pressure is great, because the barometric gradient is steep (Fig. 448).

Measurement of Air Movement. — The measurement of the direction and rate of movement of the wind is important in connection with the study of the atmosphere, wind direction being commonly determined by the ordinary *wind vane* and the rate of movement of the air by an instrument known as the *anemometer*. The commonest form of this instrument has four light metal cups mounted on cross bars. The wind strikes the hollow side of the cups and causes the cross bars to revolve. Each revolution is communicated by a vertical shaft to a cog-wheel, which is connected with a moving hand upon a dial. In this way the velocity of the wind is recorded in miles. The dial is graduated so that the movement of the wind indicates the number of miles and tenths of miles the wind has moved. The anemometer is sometimes equipped with a self-recording apparatus connected by an electric wire.

The velocities of the wind may be roughly given as follows: a light breeze commonly has a velocity of from 1 to 10 miles an hour; a strong wind from 20 to 30 miles an hour; a gale from 40 to 60 miles, and, in the case of very severe winds, as in tornadoes, the velocity is often as much as 100 or 200 miles an hour.

Local Winds

Land and Sea Breezes. — The circulation which is set up on the seashore in connection with the heating and cooling of the atmosphere illustrates one of the simplest causes of local winds. The same sort of thing may also take place on hot days along the shore of good-sized

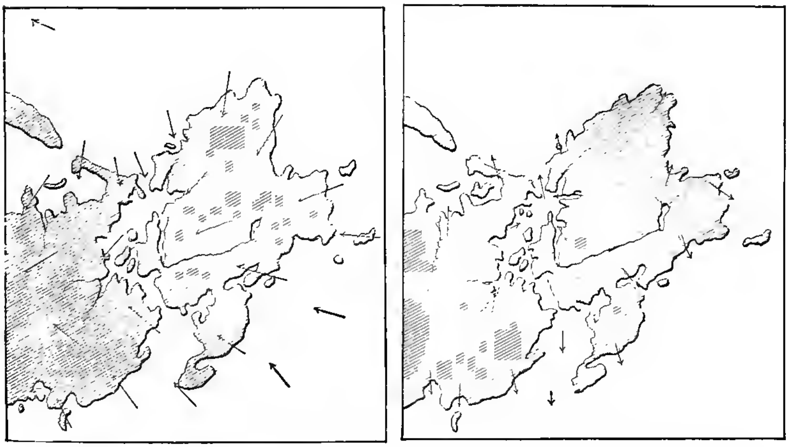


Fig. 446. — The sea breeze (left) and land breeze (right) on Cape Ann, Massachusetts.

lakes. It should be recognized, however, that the land and sea breeze are not especially common in the temperate zone, and that the subject is discussed at some length, because it so well illustrates the principle of wind circulation under the simplest conditions. These breezes rarely affect more than 10 or 15 miles near the coast.

On a fine, warm day in summer the air over the land is warmer than the air over the water. Early in the morning there may be no wind at all. Soon, however, the land is warmed by absorption. The air is warmed by radiation, conduction, and convection, which go on more rapidly over the land than over the water. The pull of gravity on the heavier air over the cool sea then results in the flowing in of a cool refreshing *sea breeze*, which displaces the lighter warm air that rests on the land. This sea breeze thus brings in cool air from over the water and therefore lowers the temperature. Before the sea breeze begins to blow, the temperature on shore may have been 80° or 90°, but, as a result of the sea breeze, the temperature falls and the rest of the day is pleasantly cool. It is partly on this account that so many people go to the seashore to spend their summer vacations. In some parts of the tropics the contrast of temperature over land and sea is so great that sea breezes are very pronounced and occur nearly every day (Fig. 446).

After the sun has set, the land radiates its heat much more rapidly than the water, and it is not very long before the temperature conditions are reversed, the land being cooler than the water and the air over the two surfaces varying accordingly. At the time when the air over the land and the air over the water reach approximately the same temperature, the sea breeze dies down because of the lack of a barometric gradient, and there is a calm. On this account sailboats are apt to be becalmed if they have not reached port before sunset. With the continuation of the process of radiation, the air over the water soon becomes warmer than the air over the land, and then gravity sets up the opposite circulation, because of the formation of a new barometric gradient. The cool air of the land slides out over the sea, causing the warmer air there to rise and setting up a *land breeze.* Sailboats which have been becalmed offshore when the sea breeze ceased may "tack" into port later in the evening when the land breeze begins to blow. The land breeze is usually warmer than the sea breeze, and on evenings and mornings when there is a land breeze, it may be uncomfortably warm even on the seacoast.

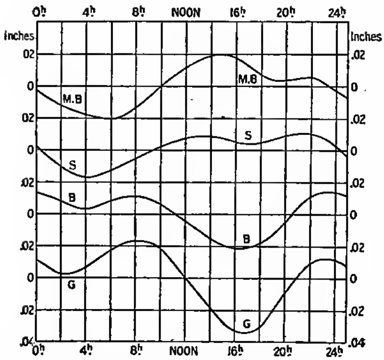


FIG. 447. — Daily range of pressure at various altitudes in the Alps. G = Geneva, 1339 feet above sea level; B = Berne, 1880 feet; S = Säntis, 8093 feet; M. B. = Mont Blanc, 15,781 feet. (Angot.)

Mountain and Valley Winds. — In hilly and mountainous regions there is sometimes a local circulation of the atmosphere similar to the land and sea breezes. This is due to the fact that the cool, heavy air slides down the slopes as the hilltops and slopes are cooled by radiation at night, thus causing the warmer air in the valley, where radiation is less, to be displaced. The cool air from the slopes is likely to move down the valley, often causing *mountain winds* that may locally gain considerable force during the night.

The opposite circulation takes place during the day when the hill slopes and the valleys are warmed and the air ascends the sides and heads of the valleys. The mountain wind down the valley at night gains strength from the fact that the winds from several tributary valleys are gathered into one main valley, while the *valley wind*, moving up the valley during the day, is apt to be weakened through being distributed into side valleys. Some valley winds, however, are very strong during the day, as where the topography is very marked and the altitude is great. An exception to the up-valley wind of the daytime is often noticed in the vicinity of glaciers, because there the air over the cold ice and the snow field settles under the influence of gravity and displaces the warmer air in the valley, so that *glacier winds* may blow down a valley from an ice tongue with considerable velocity.

Monsoon Winds

Relation to Seasonal Variations of Temperature. — The land and sea breezes, and the mountain and valley winds, are related to daily temperature changes. There are similar winds due to seasonal changes of temperature, and these, when well developed, are known as *monsoons*. They occur on some of the continents, especially in Asia, and cause a variation in direction of the wind from summer to winter.

The Monsoons of India. — The monsoon winds are best developed in India. There the great land mass of southern Asia becomes much

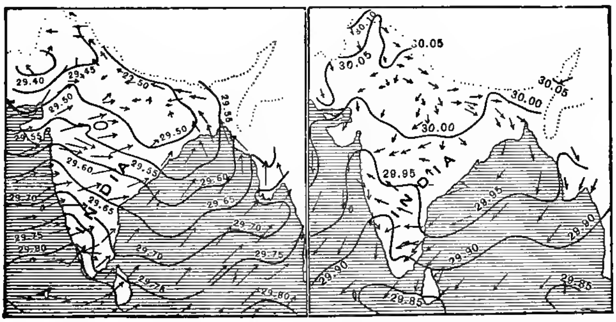


Fig. 448. — The summer monsoon of India on the left, and the winter monsoon on the right. The figures show the barometric pressures, and the lines of equal pressure, or isobars, indicate the reversed barometric gradients of the two seasons.

warmer in summer than the adjacent Indian Ocean. The air therefore blows from the ocean towards the land and is known as the *summer monsoon*. In the winter the continent and the plateau of India are cooled by radiation until their temperature is less than that of the adjacent Indian Ocean. The heavy air over the land therefore moves outward and displaces the lighter air over the ocean, forming the *winter monsoon* (Fig. 448).

Accordingly, the winds change twice a year, and the changes are so regular and the winds so steady that they were taken advantage of in early times by sailing vessels carrying cargoes to and from Europe. The ships planned to reach the Strait of Bab-el-Mandeb, at the entrance of the Red Sea, in the spring, at the time of the beginning of the blowing of the summer monsoon. As India is directly northeast of the Strait of Bab-el-Mandeb, and as the summer monsoon blows from southwest to northeast, these trading vessels were able to proceed to India with a fair wind. They discharged their goods there and took on new cargoes for transportation back to Europe, waiting until fall, when the beginning of the winter monsoon, which blows from northeast to southwest, furnished a fair wind to take their ships directly southwestward to the Strait of Bab-el-Mandeb and the Red Sea. The sailing routes in the Indian Ocean, the Bay of Bengal, and the Arabian Sea are to-day markedly under the control of the monsoons.

As winds are always named by the direction from which they blow, just as we call a man who comes from Germany a German, and one who comes from western United States a westerner, the summer monsoon coming from the southwest is often spoken of as the Southwest Monsoon, and the winter monsoon coming from the northeast as the Northeast Monsoon.

Monsoons in Other Regions. — There are similar monsoons in other parts of Asia, along the coast of China, for example, where the summer monsoon is a southeasterly wind rather than a southwest wind; but the monsoon circulation is not so well developed as in India.

The other continents, likewise, show some tendency to develop a monsoon circulation, but in most cases the regular winds are too well established to allow the recognition of the monsoons as independent winds. The seasonal changes in temperature over the continents usually result in slight changes in wind direction from season to season and not in a complete reversal of direction. Around the borders of most continents in the temperate zone the monsoon is not strong enough to destroy completely the westerly wind circulation and form regular monsoons. In the United States a fairly regular monsoon circulation can be recognized in the lower Mississippi valley, especially in Texas.

Planetary Circulation

Relation to Temperature. — The major wind systems of the earth are directly related to the distribution of temperature over the earth. In general there is a warm equatorial belt between the Tropic of Cancer and the Tropic of Capricorn, and cooler belts north and south of it. These are determined by the greater heating of the atmosphere (*a*) by the vertical rays of the sun between the tropics, and (*b*) the decreasing supply of heat with the lower and lower angle of the sun's rays to the north and south.

There is of course a direct relation of temperature to barometric pressure, the warm air in the tropical zone having low barometric pressure in contrast with the cool air and high barometric pressure to the north and south. There are also local areas of permanent high pressure and permanent low pressure at various points over the continents and oceans as a result of this relation of pressure to temperature (Fig. 449).

Accordingly, we find that the planetary circulation of the earth results in the formation of seven belts of varying atmospheric circulation. The first of these is (*a*) the belt of equatorial calms, north and south of which are pairs of belts one in each hemisphere which we

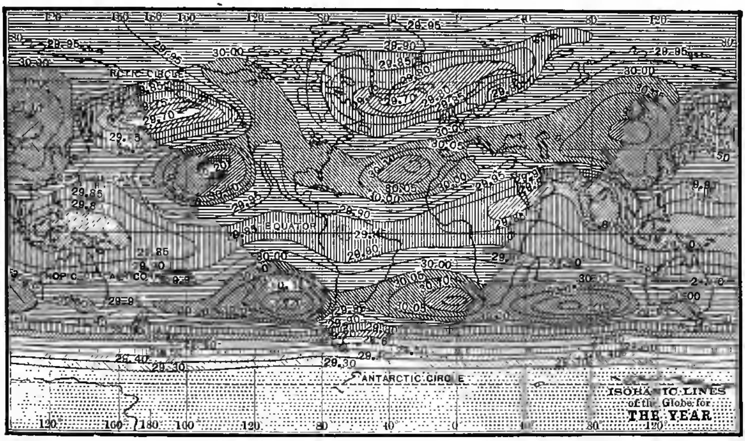


FIG. 449. — Isobars or lines of equal pressure for the year. The darkest shading represents high pressure. The figures (29.85 for example) are inches to which the mercury in a barometer rises, being highest where the air pressure is greatest. In the dark zones of high pressure, the horse latitude belt, the air is settling; it moves thence toward the low pressure belt of the warm tropical zone, forming the trade winds, and toward the low pressure areas near the poles, forming the prevailing westerlies. (Bartholomew.)

know as (*b*) the trades, (*c*) the horse latitudes, and (*d*) the prevailing westerlies (Fig. 450).

Comparison with the Circulation of Air in a Room. — The circulation of air on the earth may be compared roughly with the movement of air in a room heated by a stove. Near the stove the air is warmed, and the cooler and heavier air in other parts of the room crowds in and pushes the warm air upward. This sets up a circulation consisting of (1) a movement of air toward the stove, (2) a rise above it, (3) an upward current away from the stove, and (4) a settling of the air near the walls of the room.

The heated belt of the equatorial regions corresponds to the part of the room near the stove. There is, therefore, (1) a movement of air along the surface of the earth from the tropics toward the equator, (2) a rising in the equatorial region, (3) a movement away from the equator high above it, and (4) a settling some distance to the north and south. The winds thus set in motion affect all parts of the earth, in every zone and over every continent and ocean. All these winds are set in motion by the relations of gravity to differences in temperature between the warm tropical region and the cooler zones to the north and south.

Belt of Equatorial Calms. — In the equatorial region there is a *belt of equatorial calms* or *doldrums* caused by the rising of the warm air which has been brought in from north and south in the trade winds. There is little wind in the belt of calms because the air movement is upward instead of horizontal. The belt of calms was named in the

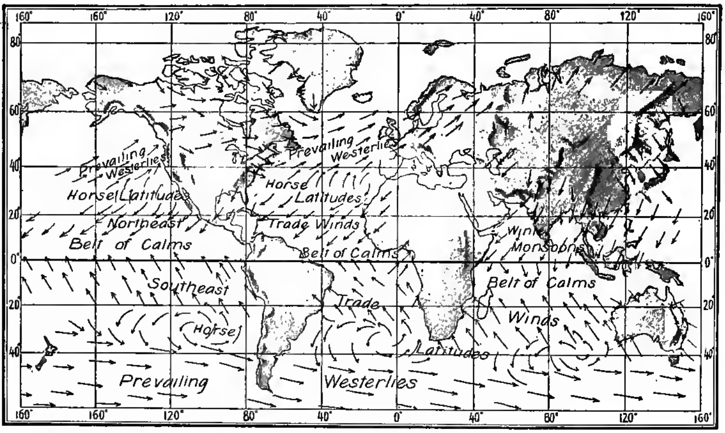


FIG. 450. — The belts of winds and calms on the earth in winter.

days of sailing vessels because of the baffling winds there which blew from no persistent direction and for no great length of time, between the much longer intervals when the ship was becalmed. The doldrum belt does not remain stationary, but migrates northward at one season of the year and southward at another with the shifting of the belt of greatest heat which is known as the *heat equator*.

Trade Winds. — The belts on either side of the doldrums are known as the *trade wind belts* because of the great steadiness of the winds over the ocean. They were named by sailors in the early days of ships propelled by the wind. Of course the wind does not blow steadily from one direction at all times in the trade wind belts; but, as is shown in Fig. 452, the prevailing wind is toward the equator. This results in (*a*) the cutting of steep cliffs on the windward sides of islands in the path of the trade winds by the surf which is always beating there, and (*b*) quiet harbours on the leeward sides. As is explained later (p. 756), the trade winds blow, not from the north and south directly toward the equator, but from the northeast in the northern hemisphere and from the southeast in the southern hemisphere because of the effect of rotation of the earth. They are therefore known as the *northeast trades* and the *southeast trades*, respectively.

With the shifting of the belt of calms northward and southward during each season, there is a corresponding shifting of the trade winds, which are farther north in summer than in winter. Places near the border of the trade wind and doldrum belts have alternate seasons of calms and steady northeast or southeast winds, with corresponding effects upon the vegetation (p. 794) and the physical comfort of the people living on the lands in these border belts.

The unusual development of the monsoons in Asia, and particularly in India, results from the excessive warming of the southern portion of this great land area in the summer of the northern hemisphere, and the consequent migration of the heat equator, and the accompanying low barometric pressure well up on the land. The outflow of cold air from India in winter strengthens the northeast trade wind, but in summer the inflow of air from the Indian Ocean is reënforced by the southeast trade wind, which extends across the equator and is there leflected so that it blows nearly parallel to the ordinary summer monsoon. At this season the northeast trades of the Indian Ocean are entirely nullified.

The air that rises in the equatorial belt of calms is divided, some of it flowing northward and some southward, high above the trade winds. These *antitrades* blow in the opposite direction from the trade winds. They may be observed on high peaks which rise above the trade winds, as in the Hawaiian Islands, and also by the movement of high clouds and of dust from volcanic eruptions.

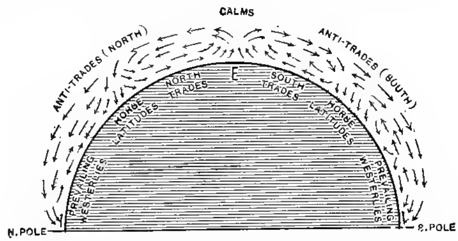


FIG. 451. — The relationships of the air circulation from the equator, E, to the poles.

Horse Latitudes.—North of the belt of northeast trades and south of the belt of southeast trades are regions known as the *horse latitudes*. These are regions which have calm weather and light, variable winds during a large part of the time. The calm condition here is due to the facts that the air is settling down from aloft, and that the differences in pressure are so slight (Fig. 451).

The belts of horse latitudes migrate northward and southward with the seasons, so that at their borders on the sides toward the equator are regions which are part of the year in the trade winds and part of the year in the horse latitude belt. At the opposite sides of the horse latitude belts, toward the poles, the borders are part of the year in the horse latitude calms and part of the year in the belts of prevailing westerly winds.

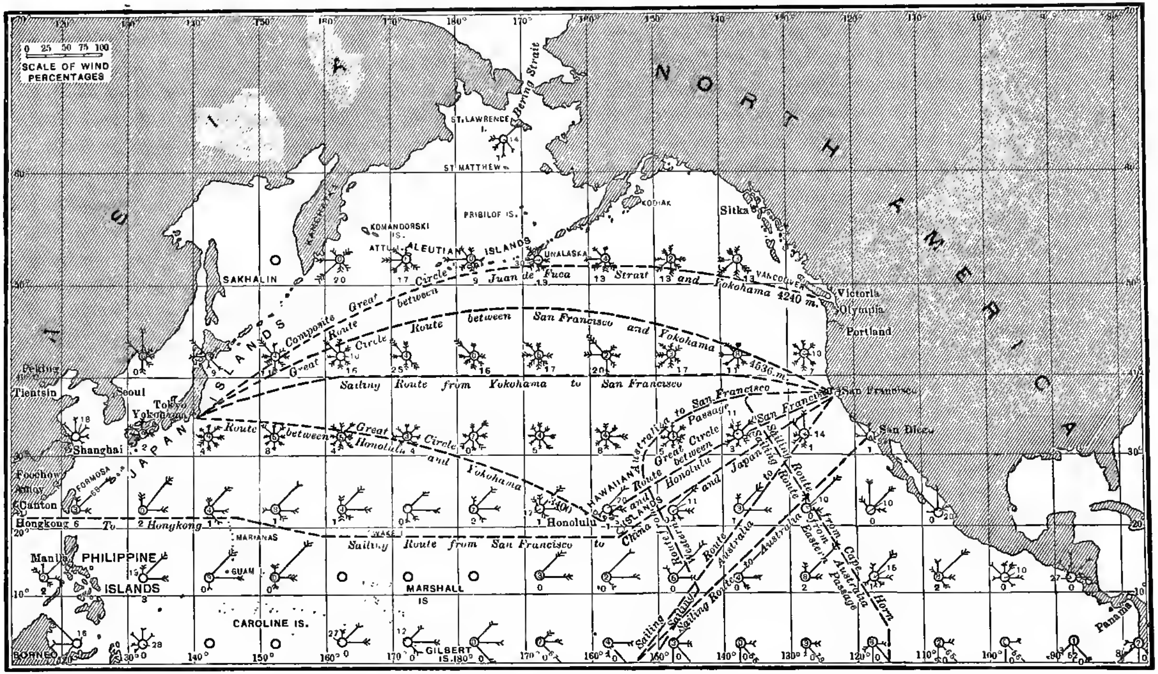


FIG. 452. — Pilot Chart of the North Pacific Ocean in November, 1909. The curved sailing route from Australia to San Francisco, in contrast with the direct route to Australia, shows the relationship to the northeast trade winds. The route swings far to the northwest in the trades and then turns east in the prevailing westerlies in order to cross the trades with the wind on the beam, instead of as a head wind. The route from Cape Horn shows a similar relationship. In the wind roses the length of the arrow shafts shows the number of hours in 100 with the wind in a given direction (measured on the scale), the number of feathers indicates the force of the wind, the number inside the circle indicates the percentage of calms and light or variable winds, and the number outside the circle indicates the percentage of gales of force 8 or over. (Hydrographic Office of U. S. Navy Department.)

Prevailing Westerlies. — These belts occupy all of the northern and southern hemispheres between the horse latitude belts and the poles. They occupy most of the temperate zone on each of the continents, and the winds and climates in the *prevailing westerlies* are therefore of most interest to civilized man.

The prevailing westerlies are supplied from the horse latitudes by air, some of which came from the equator and some from the poles. Accordingly there is a movement of air from a broad belt in the temperate zone toward the small area around each pole. This may be compared with the movement of water toward the small outlet of a wash-basin. In attempting to reach the outlet of the wash-basin, the water whirls about it. In a similar way the air whirls about each pole in what is known as the circumpolar whirl (Fig. 453). The direction in which this whirling air is turned from a north-south direction is toward the east in each hemisphere, because of an influence of the earth's rotation (explained later, p. 756). The direction of movement of the air near the horse latitudes is, therefore, converted to an easterly direction near the earth's surface in each hemisphere; and, since the air moves from west to east, these wind belts are called the prevailing westerlies. They cover the greater part of the two temperate and the two polar zones.

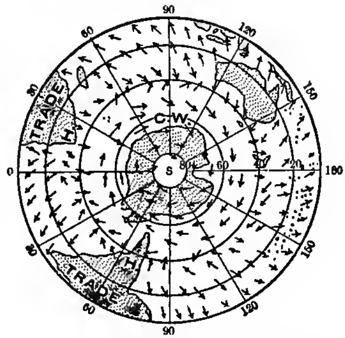


Fig. 453. — Diagram to show ideal wind circulation in the southern hemisphere near the earth's surface. Trade = trade wind belt; H = horse latitudes; C. W. = circumpolar whirl.

Variations in the Prevailing Westerlies. — Various causes interfere with these winds. They are often strongest during fine summer days, for example, on account of the heating of the lower air which then rises, being displaced by faster-moving air from a short distance above the earth's surface. After sunset when the lower air is cooled, these winds die down. Sea breezes, storms, the influence of valleys and mountains, and other topographic features also modify the direction and velocity of these winds.

The topography and the variations in temperature of different soils and rocks, and of the surfaces with or without vegetation, interfere with the movement of the air, so that the winds are usually weaker and less steady on land than over the ocean. The southern hemisphere, in which the areas of the ocean exceed those of the continents, has better-developed prevailing westerly winds than the northern hemisphere. The velocity of the winds in the southern hemisphere is such that the prevailing westerlies in and near latitude 40° south are sometimes alluded to as the *Roaring Forties*. In the southern parts of the

Pacific, Atlantic, and Indian oceans, it is possible for a vessel to sail eastward around the earth in the prevailing westerly wind belt with fair winds most of the way.

In the northern hemisphere, where the westerlies are interfered with by the large proportion of land, there is nevertheless great steadiness and velocity at some height above the earth. This may be observed by watching the upper clouds which usually move rapidly eastward, even when the wind at the surface is from the opposite direction.

Effect of Rotation on Winds. — As already mentioned, the trade winds are deflected from blowing directly northward and southward toward the equator, and the prevailing westerlies are also deflected by the influence of the earth's rotation. This is an application of what is known as *Ferrel's Law.* A body moving in any direction upon the earth's surface is deflected towards the right, if in the northern hemisphere and toward the left, if in the southern hemisphere, by the rotation of the earth from west to east. This applies to objects at any point except directly on the equator. Its most notable effect is upon the movements of the atmosphere (Fig. 454).

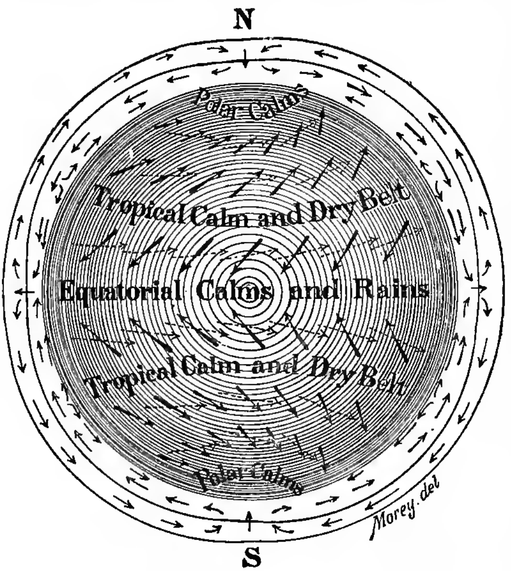


FIG. 454. — Ferrel's ideal diagram to show the atmospheric circulation in plan and cross-section. Dotted arrows show upper air currents.

The trade wind in the northern hemisphere, which is moving toward the heated equatorial region, would move from north to south if the earth were not rotating. As a result of Ferrel's Law, however, this wind is deflected towards the right, and therefore blows from northeast to southwest and is known as the northeast trade wind. The deflection is spoken of as *right-handed deflection*, since the departure from movement directly towards the equator is toward the right hand as one faces the equator. The trade wind of the southern hemisphere, which is affected by *left-handed deflection* in a similar way, becomes a southeast wind rather than a south wind. The prevailing westerly winds of the northern and southern hemispheres are affected respectively by right-hand and left-hand deflection and, therefore, become westerly winds.

The effect of rotation upon the ocean currents is well established, as in the movement of the Gulf Stream in the North Atlantic Ocean (p. 693), but the deflection of rivers is so slight that the application of Ferrel's Law is not fully accepted by all persons, although it has been pointed out that rivers in the northern hemisphere have cut higher banks on one side in some places, as if they were deflected by the earth's rotation.

Seasonal Migration of Wind Belts. — The northward and southward migration of the wind belts results from the fact that the earth is

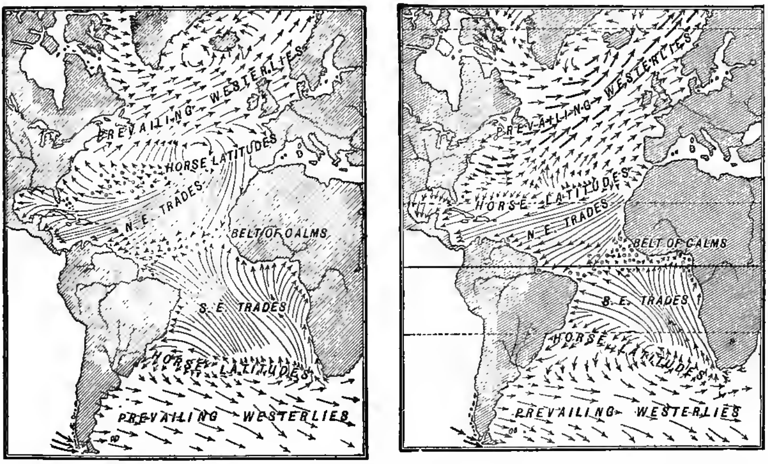


FIG. 455. — Wind belts of the Atlantic in winter (right) and in summer (left), showing migration of wind belts with shifting of heat equator. Length of arrows indicates steadiness; double line, strong winds; circles, calms. Prevailing westerlies in north Atlantic are best developed in winter when cold air from North America flows outward. (After Köppen.)

inclined at an angle of $23\frac{1}{2}°$ on its axis and revolves about the sun in this inclined position, so that the sun's rays are vertical at the mathematical equator only twice a year. This is at the time of the vernal and autumnal equinoxes; and the sun's rays are vertical at one tropic three months earlier and at the other tropic three months later. Accordingly, the zone of greatest heat migrates with the season of the year; and the heat equator is sometimes north of the mathematical equator and sometimes south of it. As a result of the unequal heating of the continents and oceans and of the air above them, the heat equator does not exactly correspond to the mathematical equator, even at the time of the equinoxes. It is north of the true equator in some parts of the world and south of it in others (Fig. 455).

At all seasons, therefore, the widths of the belts of doldrums or equatorial calms, trade winds, horse latitudes, and prevailing westerlies vary over the continents and over the oceans. These belts all shift with the season, being farther north in the northern hemisphere in our summer, and farther south in the southern hemisphere during our winter. The effect of this migration upon the border belts has already been noted. It causes some regions to have two seasons, one of them calm and the other windy, one wet and the other dry, depending upon the time when these regions are in the belt of equatorial calms or horse latitudes, or in the belt of trade winds or of prevailing westerlies. The migrations are regular, however, so that these border regions have a recurrence of windy or calm, dry or rainy, seasons. The middle portion of each of these belts, however, and the larger part of the belts of prevailing westerly winds, have no corresponding change in their wind régime, although their temperatures and the regularity of their winds vary more or less with the seasons. The seasonal migration of wind belts causes some exceedingly important variations in climatic conditions.

Cyclonic and Anticyclonic Areas. — The development of extensive areas of cyclonic and anticyclonic character over oceans and lands has a notable effect upon the regular winds of the earth. The nature and cause of the cyclonic areas is explained more fully in the following chapter (p. 765). It is sufficient here to state that cyclonic areas are those in which the air moves around toward a region of low pressure, with the winds blowing in all directions toward the centre; and that anticyclonic areas are areas in which the air moves outward from a region of high pressure, with winds blowing in all directions from the centre. The development of such areas results in an interference with the regular winds, but cyclonic development is relatively rare in the belts of trade winds and is found chiefly in the prevailing westerlies.

These cyclonic and anticyclonic areas completely nullify the prevailing westerly circulation at times, and greatly strengthen it at others. They move in the general direction of the prevailing winds.

For references to literature on Winds, see pp. 781–782.

CHAPTER XXVI

STORMS

Cyclonic Storms

Nature of an Area of Low Pressure. — The characteristics of a low pressure area are as follows, and may be illustrated by the study of a weather map of the United States for a typical day in winter. Figure 456 shows an area where the barometric pressure is low. The longer name *low pressure area* is generally abbreviated to the term *Low*, and this is done on the map. Outside this centre of low pressure, or Low, the mercury in the barometer is higher. The distribution of pressure is indicated by lines of equal pressure, or *isobars*. Some distance southeast of the Low, which is in Canada near the Rocky Mountains, are two areas marked *High*, and these are areas of maximum pressure for that part of the United States. The direction in which the wind is blowing is indicated on Fig. 456 by arrows which fly with the wind, and the air is moving from all directions towards the low pressure area. In addition to the isobars — heavy lines on the map which indicate equal pressure — there are dashed lines which indicate equal temperature, — isotherms (p. 723). The relation between the isotherms and isobars and the precipitation of rain in the vicinity of areas of low pressure is important.

Eastward Movement of an Area of Low Pressure. — On the weather map for the following day (Jan. 8) the Low has moved eastward, its path being indicated by a chain of arrows from southwestern Canada to Lake Superior. Near it the map is shaded to indicate that rain has fallen during the past 24 hours. The arrows show that the air is still blowing in towards the centre of this Low.

In the weather map for the third day (Jan. 9, Fig. 456) the storm has moved still farther eastward and it is now central in the Province of Ontario, east of Lake Huron. If we had maps for other days, we should be able to trace this Low out over the Atlantic Ocean and possibly across the British Isles and Europe into Siberia, although it might merge with some other low pressure area on the way, or completely disappear.

Such a low pressure area as is shown in these maps is known as a *cyclone* or *cyclonic storm*, which may be defined as an area of low air pressure toward which winds blow from all directions and in which rain frequently falls.

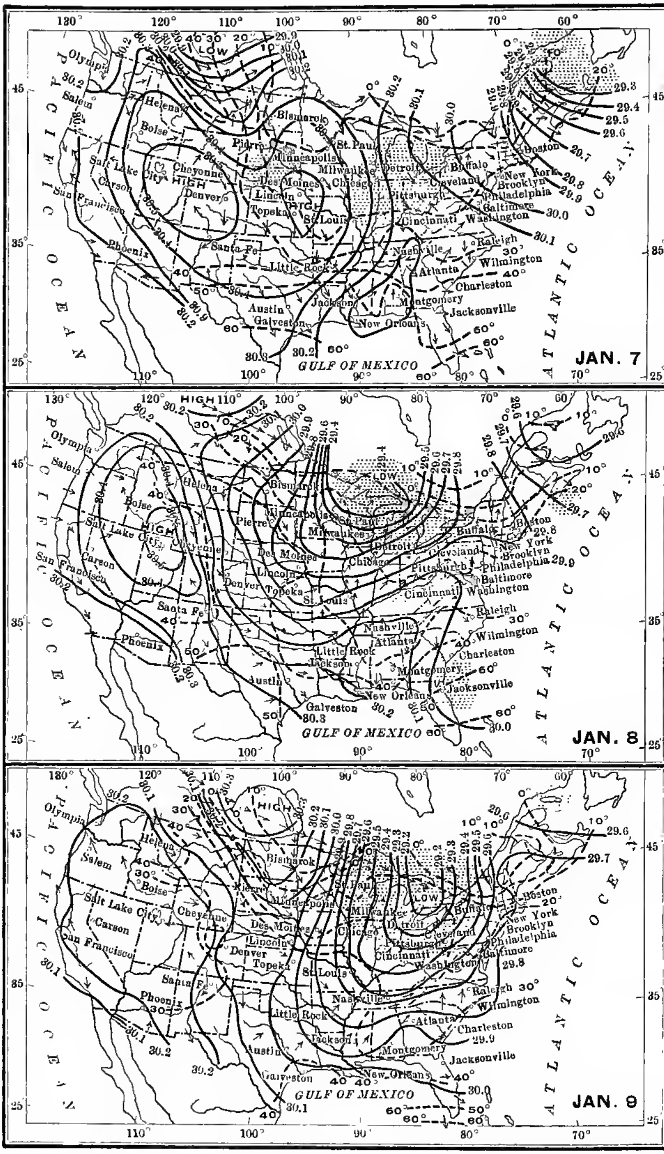


FIG. 456. — Weather maps of three successive days in 1893, showing isobars (heavy lines), isotherms (dotted lines), wind direction (indicated by arrows), and areas of rain (shaded). The path of one Low from Western Canada to New England is indicated by a chain of arrows. (After U. S. Weather Bureau.)

Difference between Cyclonic Storms and Tornadoes. — A cyclone or cyclonic storm should be carefully distinguished from that type of violent wind of small area which is known as a tornado. We use the name tornado for a violent destructive storm of small area, and the

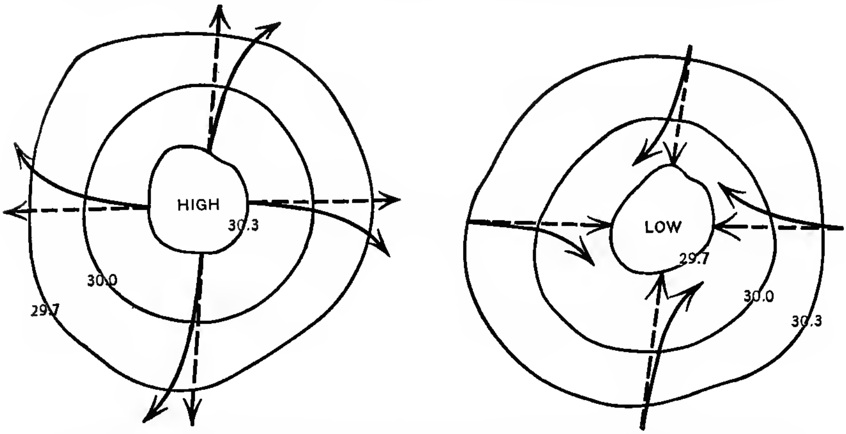


FIG. 457. — The winds blowing down a barometric gradient toward a cyclonic storm centre (right) with deflection due to the earth's rotation. The opposite wind circulation (left) in an anticyclone. (Milham.)

name cyclone or cyclonic storm for the area of low pressure, which is of much larger size and in connection with which there may be nothing violent. The name cyclone comes from the fact that the winds blow inward and around the centre of an area of low pressure, which is itself moving.

Relation of Pressure to Cyclonic Storms. — Within the Lows the barometric pressure does not vary greatly, the range in Fig. 457, for example, being from 29.7 inches at the centre of the Low to 30.3

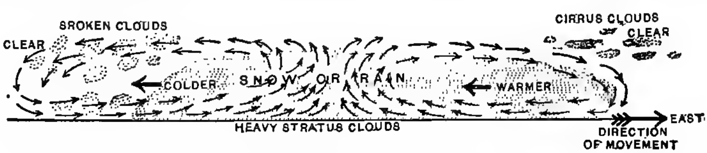


FIG. 458. — The inflowing and rising air in a cyclonic storm, with distribution of clouds and precipitation.

inches at one side. The isobars always encircle areas of low and of high pressure.

Relation of Winds to Cyclonic Storms. — The relation of winds to a Low is well indicated in the diagrammatic sketch (Fig. 458), where it is seen that the light air in the middle of the Low is forced to rise by the flowing in of the heavier air on either side, which is descending the barometric gradient toward the centre of the Low.

A commonly observed phenomenon is the reversal of the direction of winds in connection with the passage of cyclonic storms. Suppose, for example, that we are some miles east or southeast of the centre of a Low. We then have a southeasterly or southerly wind, because the air is moving toward the centre of the cyclonic storm. Later the cyclonic storm has moved far enough east or northeast of us to leave us some miles west or southwest of its centre. At that time we have a

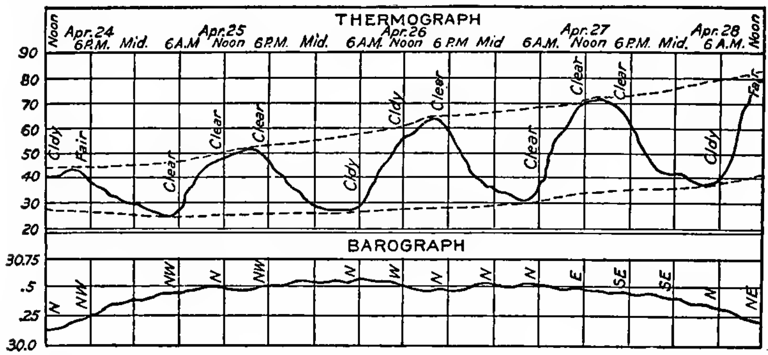


FIG. 459. — Thermograph and barograph curves with indication of direction of winds and alternation of clear and cloudy weather. Normal diurnal curves, of large range, with a rise in the mean temperature and in the maxima and minima from day to day under the clear sky of a spring anticyclone. At the beginning of this spell (April 24) the cool wave in front of the approaching anticyclone brought lower temperatures, while the warming increased in the light winds near the centre of the High. The rise in the mean temperature from April 25 to 27 is shown by the rise of the dotted temperature helt. (Ward.)

westerly wind, because the air is moving eastward toward the centre of the Low (Fig. 459).

Relation of Clouds and Precipitation to Cyclonic Storms. — The relation of clouds to the cyclonic storm (Fig. 458) is a natural one, the centre of the Low having heavy nimbus clouds because the rising air is cooled sufficiently to have its relative humidity increased to the dew point at no great height above the earth's surface. After the air has moved upward over the centre of the Low, and outward in either direction, the clouds are likely to be more broken, and at some distance there will be high cirrus clouds and clear weather (Fig. 460).

The relation of rain to a cyclonic storm is also a simple one. There is usually precipitation of rain near the centre of the cyclonic storm because of the continuous process of condensation which goes on in this cloud area, until drops of water too large to float are formed, and fall to the earth's surface. In eastern United States the rain is likely to be in the southeast quarter of the cyclonic storm, because the air from the south and east is moving northward and is, therefore, being cooled. It will cause precipitation as rain or snow sooner than the air moving toward the centre of the Low from the north or west, because the latter is moving southward and is having its capacity for moisture increased by being warmed (Fig. 461). The precipitation in connection with the eastward movement of the Low of Fig. 456 brings rainfall on successive days to Michigan, Ontario, and western New York.

Relation of Temperature to Cyclonic Storms. — The relation of temperature to cyclonic storms is a result of the variations in wind

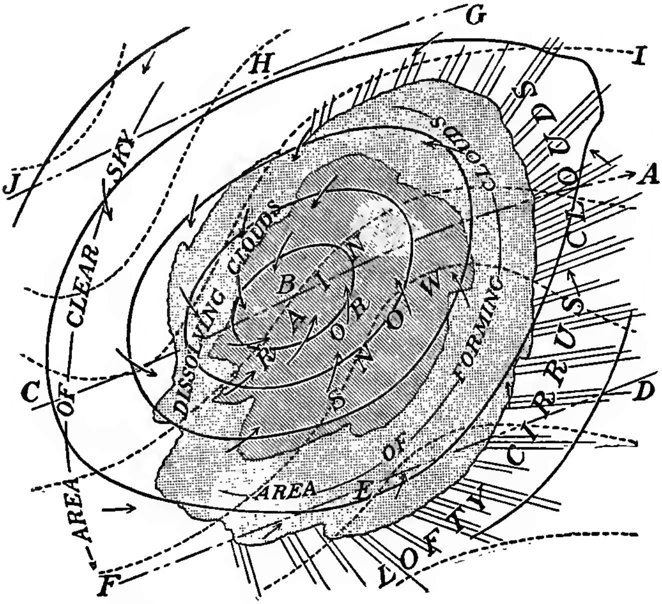


FIG. 460. — Diagram to show the relationships of clouds to the different parts of a low pressure area. (Ward.)

direction. It is apt to be warm when the southerly wind is blowing, and cool or cold when there is a northerly wind.

Anticyclones. — The areas of high pressure marked High on Figs. 456, 461, and 463 have the wind blowing outward in all directions from the centre and are usually called *anticyclones*, because the conditions within them are just the reverse of those in cyclones. The sky is generally clear or fair, and there is not likely to be rain. Anticyclones are cold in winter, but warm by day in summer, with cooler nights. Figure 462 shows the usual circulation of air in an anticyclone. The anticyclones move eastward as the cyclonic storms do, in many cases crossing the continent of North America and the Atlantic Ocean to Europe.

Normal Movements of Cyclones and Anticyclones. — In the temperate zones the belts of prevailing westerly winds are visited periodically by a succession of cyclones and anticyclones. Figure 463 shows the

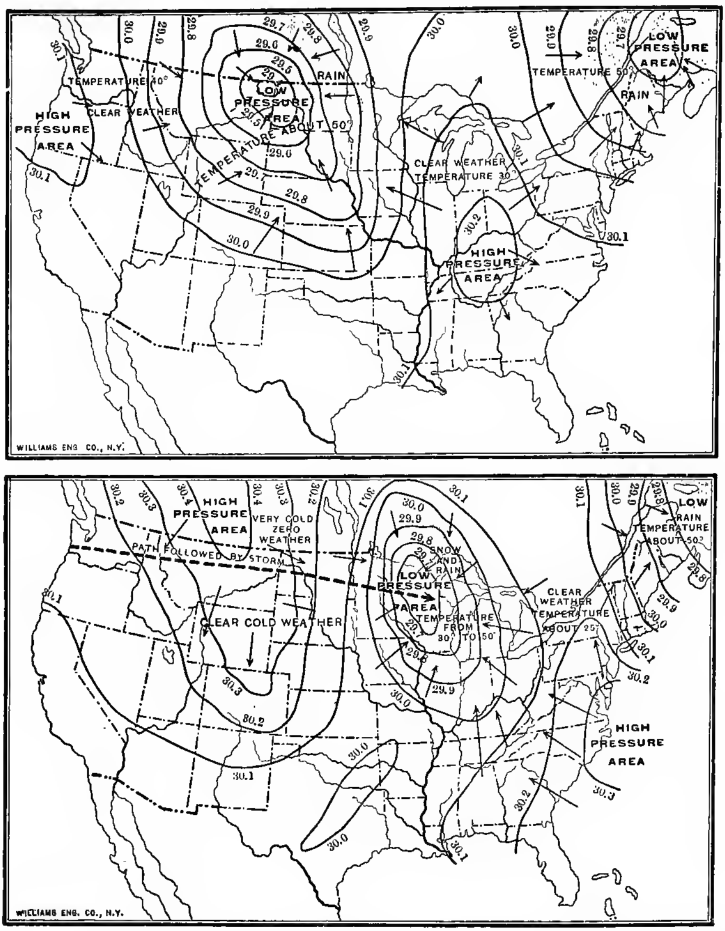


FIG. 461. — Upper map shows area of winter rainfall (stippled) in the eastern part of a low pressure area in Minnesota and North Dakota. Lower map shows the same low pressure area a day later when it has moved eastward, bringing rain to Wisconsin and adjacent states. (After U. S. Weather Bureau.)

positions of a series of Lows and Highs in the northern hemisphere on January 30 and 31, 1914. In the northern United States, two low pressure areas with an intervening High are likely to pass any given place at intervals of from 3 to 7 days in winter. If you watch the maps published by the United States Weather Bureau, you will see a movement of areas of high and low pressure similar to those in Figs. 456, 461, and 463. The passage of these areas of low pressure is indicated by the rise and fall of the barometer, and the curve in Fig. 464 shows the change of pressure at one point during a week. It is by means of a study of the barometric pressure over the whole of the United States that it is possible to predict what the weather will be, because of the regularity of movement of these cyclonic storms and their relationships to temperature, winds, and precipitation. In winter, especially, cloudy weather, with rain and higher temperatures, usually accompanies the cyclonic storms and clear and

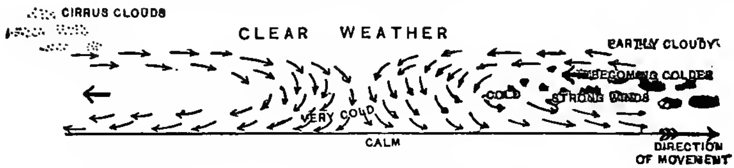


FIG. 462. — The descending and outflowing air in an anticyclone.

colder weather the anticyclones, the wind direction of course varying as these Highs and Lows pass.

There are several paths which are commonly followed by the low pressure areas of United States (Fig. 465). Most of the Lows seem to originate either in the northwest or in the southwest, but many doubtless reach the western United States from the Pacific Ocean. In each case they move eastward, usually crossing the Middle West in the vicinity of the Great Lakes and following the St. Lawrence valley to the Atlantic Ocean. The average velocity of movement of the storm centre is between 500 and 1000 miles a day.

It should not be thought that there is stormy weather in connection with all low pressure areas. Some cyclonic storms have light wind because the pressure is not very low, and the barometric gradient is not very steep. Such Lows are likely to have little if any rain. These weak cyclonic storms sometimes die out entirely, and sometimes develop into exceedingly vigorous storms. On this account the prediction of the weather is sometimes erroneous, but the movement of cyclonic storms is generally so regular that most storms are accurately forecasted.

Reason for Cyclonic Storms in Prevailing Westerlies. — The reason for the development of the cyclonic storms in the west wind belts is not entirely understood, but it is clear that the cyclones and anticyclones move like great eddies in the prevailing westerlies of the northern and southern hemispheres. The blowing in of the air towards the centre of the Lows is like the movement of water in an eddy in a river.

Likewise, while the cyclonic storm is moving eastward (Fig. 466)

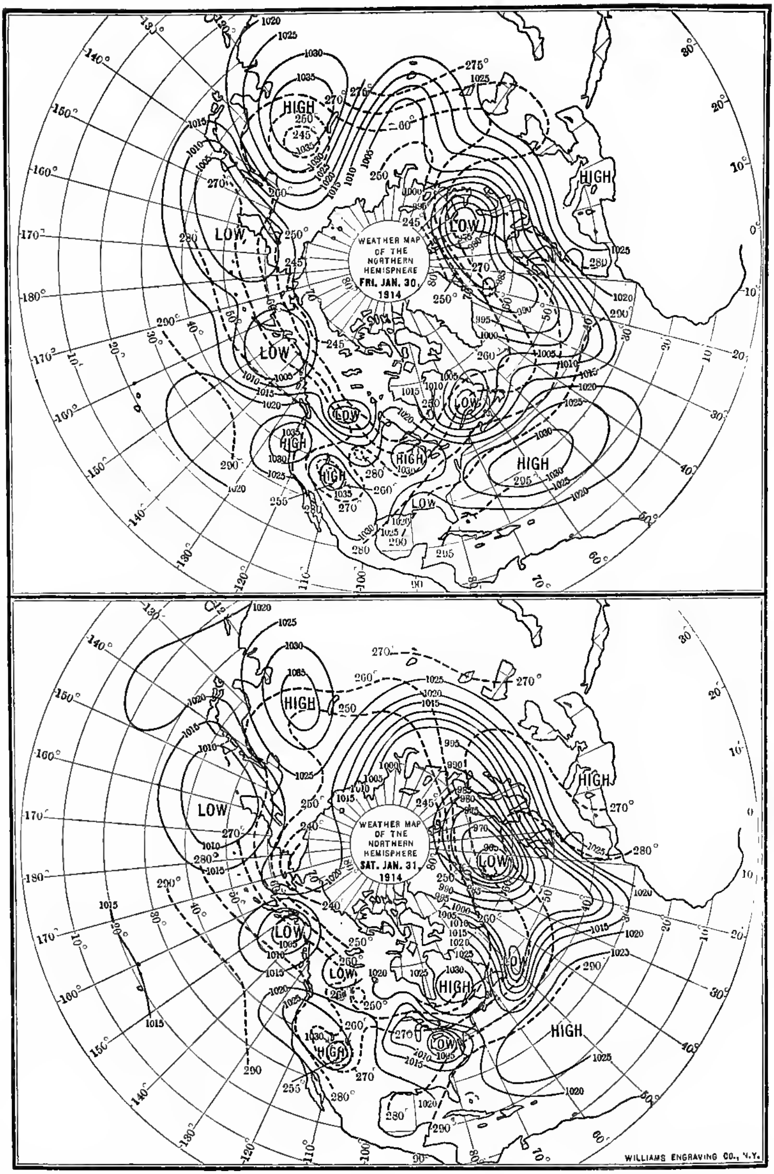


FIG. 463. — Weather map of the northern hemisphere on two successive winter days in 1914. Continuous lines are isobars. Pressures are expressed in millibars (1000 millibars = 29.53 inches). Dotted lines are isotherms. Temperatures are expressed in absolute units (freezing point = 273°). Note eastward progress of areas of high and low pressure. (After U. S. Weather Bureau.)

with the prevailing westerlies, the air within it is eddying from all sides towards its centre, and the air in the eastward-moving anticyclone is moving outward in all directions from the centre.

The development of cyclonic storms in the prevailing westerlies may sometimes be related to the heating of the air and its consequent rising over the heated place, somewhat as the air rises over a stove when the heavier air is drawn in towards the centre. The chief objection to this theory is the fact that cyclonic storms are most common and are best developed during the winter, when local excess of temperature should be less likely to occur. It seems likely, however, that the cause of most of our high and low pressure areas is to be sought in the conflict and congestion of air currents from different directions and with different conditions of temperature, — this conflict taking place above, it may be some miles above, the earth's surface.

Whether the cyclones and anticyclones are due to warming of the air or to conflicts of air currents or to some other cause, it is clear that some parts of the atmosphere have a lower pressure than others, and, because of the influence of gravity, the air flows toward these places of low pressure, starting a whirl which we known as the cyclonic storm.

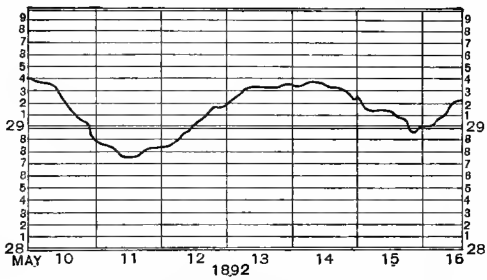


Fig. 464. — Curve showing change of pressure for seven successive days in summer in central New York with the passage of two cyclonic storms.

Relation of Cyclones and Anticyclones to Local Weather. — It has already been pointed out that the wind changes during the passage of cyclones and anticyclones, and that on the east side of a cyclonic storm the wind is generally easterly in direction, on the south side generally southerly, and between the cyclone and the succeeding anticyclone from a westerly direction. These winds, however, do not move straight towards the centre of the Low. They are turned by the effect of the earth's rotation so that they blow spirally; and if the difference in air pressure between the High and the Low is great, they blow with considerable force. The rising of the air near the centre of the Low and the settling of the air near the centre of the High separate the reversal of winds during the passage of cyclonic storms.

The influence of the warm south wind and the cool north wind upon the weather during the passage of an area of low pressure has likewise been pointed out. During the passage of anticyclones the air settles near the centre, and, in moving away from the centre, usually causes pleasant weather in summer. During the passage of an area of high pressure in winter the weather may be extremely cold. It also happens

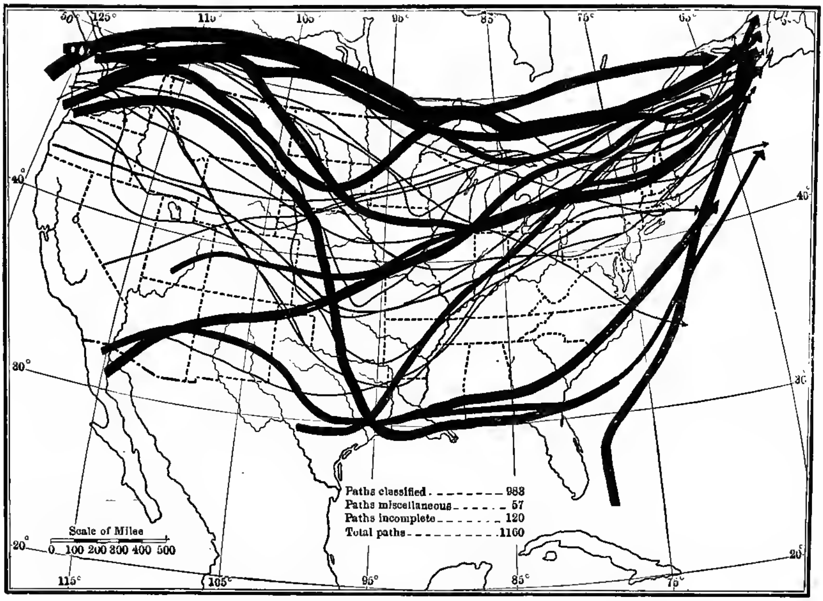


FIG. 465. — Paths of cyclonic storms across the United States. (Van Cleef.)

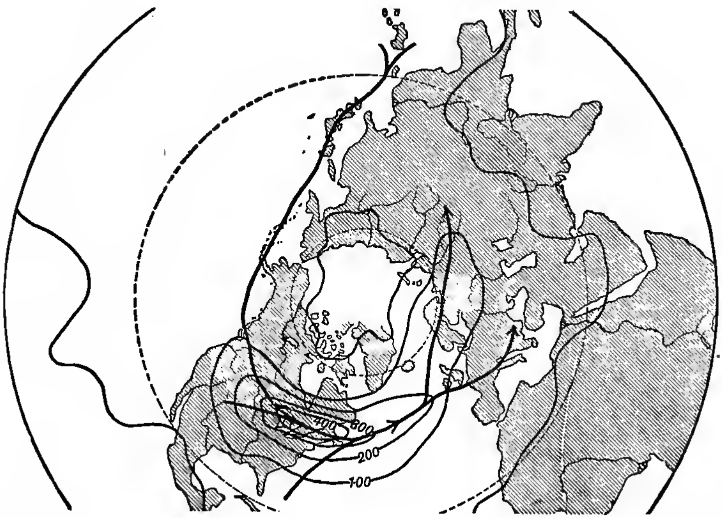


FIG. 466. — Diagram to show the average path of storms in the northern hemisphere. The figures show the total number of storms from 1878 to 1887.

that the ground is cooled far more by radiation through the clear air of the anticyclone than the cloudy air of the cyclone and that the summer weather is consequently cooler while a High is passing. Since descending air is warmed, the cause of anticyclonic cold is to be sought in active radiation, rather than in the descent of cold from aloft.

Cyclonic Storms and Rain. — The reason for clear weather in connection with anticyclones is that when air is settling, it is growing drier. It is, therefore, having its capacity for moisture increased, as is always the case when descending air is warmed by compression. It is for this reason that there is usually little or no rain in connection with the passage of an area of high pressure. The opposite is true, however, in the areas of low pressure, where the cooling of the air as it rises causes condensation of vapour and the formation of clouds and rain. In a well-developed cyclonic storm the area of cloudy and rainy weather may be as much as a thousand miles in diameter (Fig. 467).

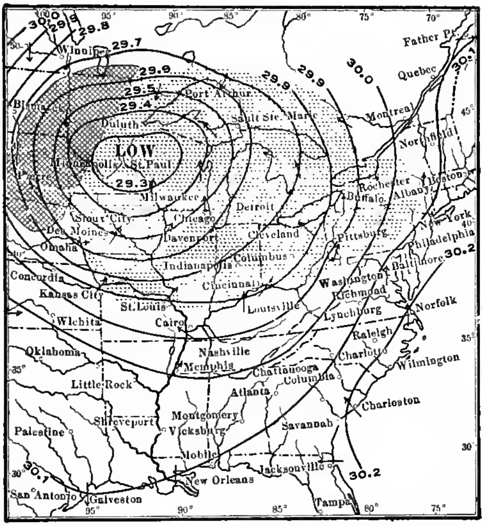


Fig. 467. — Weather map for a winter day, showing rainfall east and south of the Low and snow to the northwest (*a*) where it is cooler in North Dakota because farther north and (*b*) in Nebraska and South Dakota because it is higher than near the centre of the Low in Minnesota. (After U. S. Weather Bureau.)

In addition to this there is also rain when the air is forced to rise over highlands (Fig. 468). The west wind in a cyclonic storm may, therefore, bring rain when it strikes the western slope of the Appalachian Highland; but there will, likewise, be rain if the east wind is forced to rise over the eastern slope of the Appalachians. In New England a Low may be situated just west of Boston, and the winds blowing in from the northeast, east, and southeast will be heavily laden with vapour because they have been blowing over the surface of the ocean. When these vapour-laden winds rise in the cyclonic storm, they are cooled sufficiently so that the dew point is reached and some of the vapour is condensed. It is very common in New England to have heavy rainfall and strong winds in connection with just these conditions, and because of a common northeast wind these are spoken of as *northeast storms* or *northeasters*. This prevalence of rain in connection with the northeast quarter of the cyclonic area is a direct result of the influence of the ocean.

In connection with the condensation of water vapour to form clouds and rain, there is a development of latent heat (p. 722), and this helps to keep the temperature of the air from falling. Very commonly, cyclonic storms increase in violence as they pass over the Great Lakes and out over the ocean. One reason for this probably is that so much more vapour is supplied over these bodies of water that the heat from its condensation helps to cause lower pressure and, therefore, a more rapid inflow and rising of air. Indeed, a cyclonic storm may be

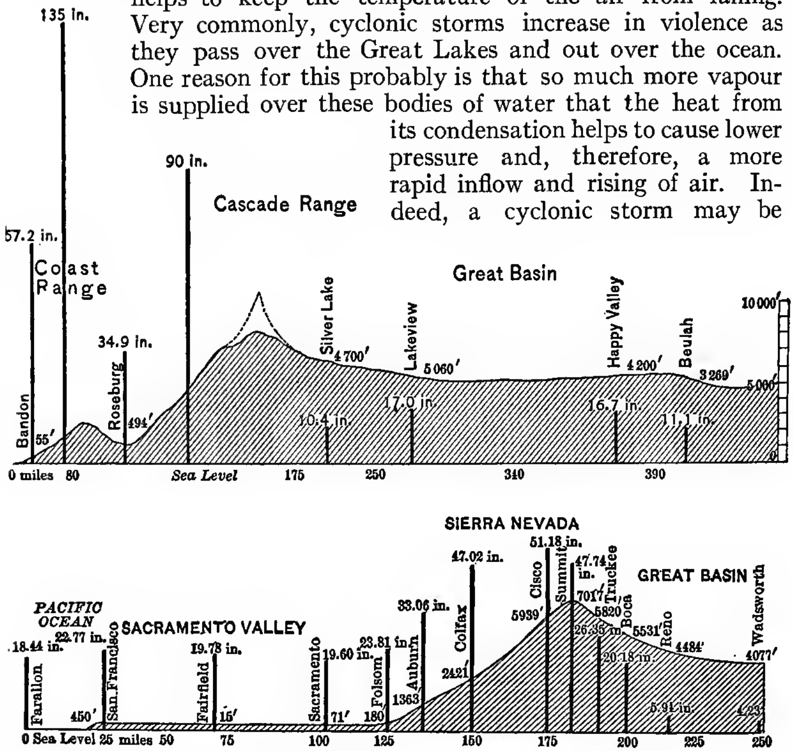


FIG. 468. — The relation of annual rainfall in the prevailing westerlies to the Coast Range and Cascades in Washington and the Sierra Nevada in California. (Bowman.)

thought of as a great engine, because it furnishes some of its own energy as the vapour condenses.

Cold Waves and Blizzards. — The west and northwest winds which follow in the rear of vigorous winter cyclones are often strong and very cold. Such cold winds accompanied by snow are called *blizzards* in Dakota and *northers* in Texas, though northers may take place without snow. The air moves with great velocity because there is a marked difference in the barometric pressure between the cyclone and the anticyclone, the barometric gradient sometimes being so steep that the wind blows 40 to 60 miles an hour. These blizzards and northers are often very destructive of life. Because of the intense cold and fierce snow squalls which accompany them, whole herds of sheep and cattle are often lost, and men sometimes lose their way in the blinding snow and are frozen by the fierce cold. In the northeastern United States there are occasionally mild forms of blizzard.

During the approach of a well-developed anticyclone following a well-marked cyclone in the eastern United States, we sometimes have a very rapid fall in temperature during the winter. When the fall in temperature reaches or exceeds a certain definite number of degrees, this is known as a *cold wave.* During a cold wave, a great body of cold air spreads over the country, sometimes even extending southward to the Gulf of Mexico. The area covered by one cold wave

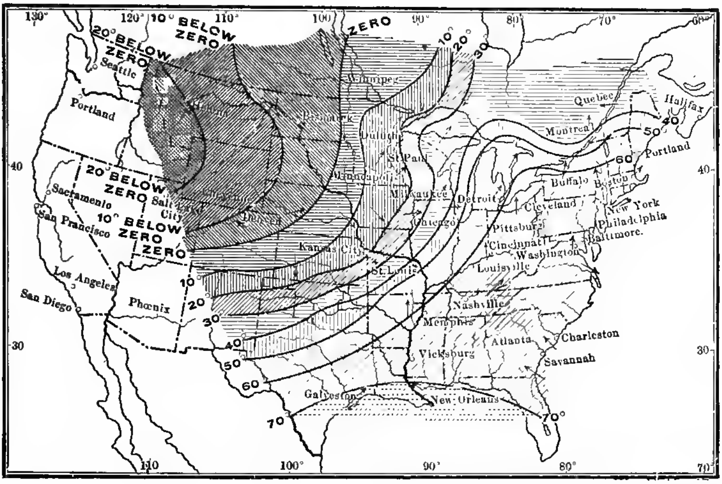


FIG. 469. — Map of a cold wave in the month of November. Arrows show wind direction. (After U. S. Weather Bureau.)

is shown in Fig. 469, where a large portion of the United States west of the Mississippi River and north of St. Louis had temperatures from freezing to 20° below zero. During a cold wave a blanket of air descends from the cold northern portion of the continent and perhaps partly from aloft (Fig. 462). Since it contains little water vapour and is warming as it spreads out, the weather accompanying it is clear and dry. Throughout a cold wave, radiation proceeds rapidly, causing very low temperatures in winter, and perhaps unseasonable frosts in fall and spring.

In Europe, certain combinations of cyclonic and anticylonic conditions also give rise to cold winds. These winds are called by various names. The *mistral* in southern France and the *bora* along the eastern shore of the Adriatic are the best known examples.

The Sirocco. — Another type of wind in connection with the passage of cyclones and anticyclones in the eastern United States is also so distinctive as to deserve a special name. This is the opposite of the blizzard and is known as the *sirocco*. It is a southerly wind, which

Fig. 470. — Photograph of a flash of lightning. (Milham.)

causes oppressively warm weather in summer and unseasonable warmth in winter. In winter the blowing of the sirocco results in the so-called " January thaw " and in unseasonable melting of the snow. During the summer the sirocco often accompanies the development of thunderstorms and tornadoes.

Chinook and Foehn Winds. — Sometimes when a cyclonic storm is east of the northern Rocky Mountains, the air which is descending the eastern slope of the mountains, on its way toward a low-pressure centre, is felt as a brisk, dry, warm breeze. It is known as the *chinook.* In descending rapidly the air is warmed by compression, just as the air in a bicycle pump is warmed. This warming lowers the relative humidity until the air becomes drier than before. Some of the best winter ranges for cattle at the western edge of the Great Plains are at the mouths of valleys where the chinook winds from the mountains evaporate the snow and leave the grass uncovered for cattle when the rest of the plains are snow-covered.

The *foehn* is of exactly the same nature. In Switzerland it was formerly believed that this wind came from the Sahara and was dry on that account. It has no relation to dry regions, however, but is dry because it is warmed by compression and has its capacity for moisture increased and its relative humidity lowered in consequence. It not only evaporates water and removes the snow with remarkable rapidity, but it dries out the wood in buildings. If situated where the foehn wind blows frequently, houses may become so dry that fires are greatly to be feared. Whole villages in Switzerland have been wiped out by fire which started at a time of foehn winds when the buildings were exceedingly dry.

Fig. 471. — Weather map showing a Low in eastern Canada in July with thunder showers (small arrows west of Boston) in its southern portion in the afternoon. (After U. S. Weather Bureau.)

Thunderstorms. — Thunderstorms commonly develop locally in areas of low pressure and usually in the southern portion of the Low, where warm, humid air is slowly moving northward (Fig. 471). A day with such weather conditions is muggy and oppressive. As the ground is warmed during the day and the air above the ground is warmed, the humid air rises and cumulus clouds appear. In the latter part of the day these clouds become larger and darker, changing to *cumulo-nimbus,* sometimes rising in rolling, surging masses a mile or more above a level base. Finally, rain will fall from such clouds, and thunder and lightning are produced. *Lightning* (Fig. 470) is electricity generated in air currents which swirl about while the vapour is rapidly condensing. Electricity gathers in the clouds until a spark passes from one cloud to another, or from the clouds to the earth. *Thunder*

FIG. 472. — Destruction by tornadoes. Upper view (W. L. Ikenberry) shows laths driven into house at Mt. Morris, Ill. Lower view (A. W. Dunwiddie) shows house turned upside down near Janesville, Wisconsin.

is the noise caused by the explosive effect of the rapid heating of the air by the passage of the electric spark of the lightning. The rolling of thunder is merely the result of echoes among the clouds or among mountains.

Thunderstorms may cover an area as large as several states, but are sometimes only a mile across. They travel eastward in the prevailing westerlies at the rate of 20 to 50 miles an hour, and in extreme cases the thunderstorm may last from 2 to 10 hours. The thunderstorm differs from the ordinary rain storm in having very heavy rain, a strong wind squall, and lightning. Hail not infrequently falls during severe thunderstorms.

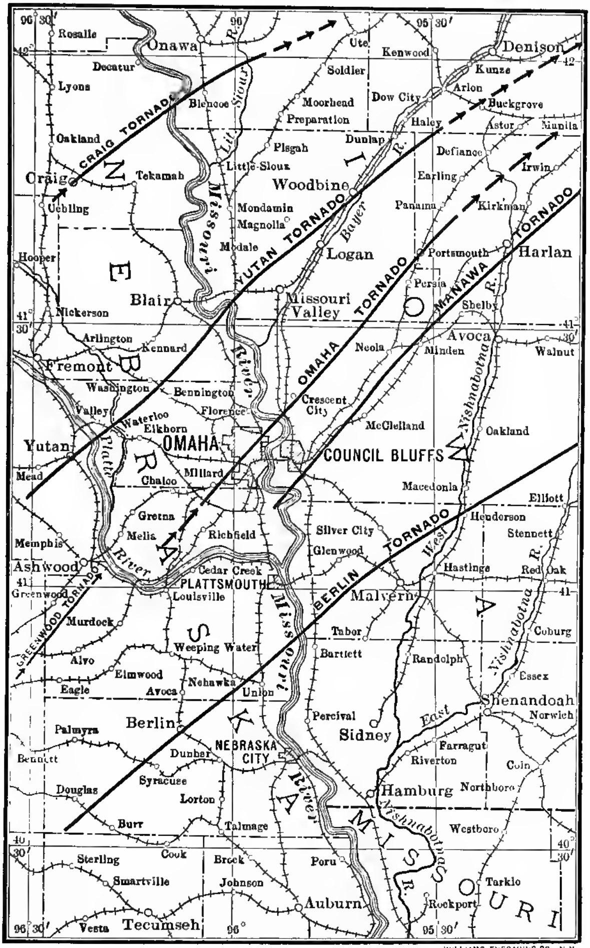


FIG. 473. — The paths of five tornadoes in Nebraska and Iowa in 1913. (Condra.)

Thunderstorms occur almost every day in the equatorial belt of calms. They are also frequent in mountains, for there the air may rise on a hot day in the ascending valley wind, until clouds gather and develop into thunder-storms. In arid lands such storms are sometimes accompanied by rapid condensation of vapour and by such heavy rain that they are spoken of as *cloudbursts*. In cool northern lands, such as Alaska, thunder and lightning rarely occur, because the temperature is too low.

FIG. 474. — A house after one wall was blown out during a tornado.

Tornadoes. — In the southern parts of low-pressure areas the conditions which cause thunder showers also sometimes cause tornadoes. These occur when the warm, humid, lower layers of air brought by southerly winds have cooler air wedged in below them by winds from the west. As the lower air rises, a whirl starts near the centre of the rising air, and winds blow with great force. Heavy rain, and often hail, fall; and there is thunder and lightning. Tornadoes sometimes occur in groups as thunderstorms do, several of them often developing in the same general district on the same day, as is shown in Fig. 473, which indicates the courses of five parallel tornadoes across Nebraska and Iowa in 1913.

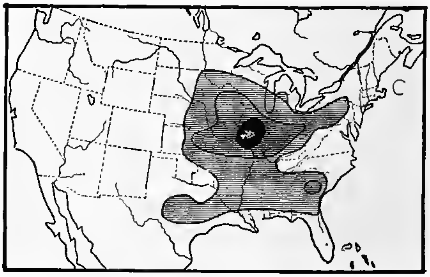


FIG. 475.—Distribution of tornadoes in the United States from 1794 to 1881. Darkest shade more than 35, medium shade 25 to 35, lightest shade less than 25.

The winds accompanying the whirl of a well-developed tornado are so strong as to overturn houses (Fig. 472), pick up heavy objects and carry them long distances, uproot trees, and cut broad swaths through a forest. At the centre of the tornado whirl there is usually a funnel-shaped cloud. Here a partial vacuum may be formed, and, as it passes, the air inside of houses sometimes expands with sufficient force to blow out windows and even the walls of houses (Fig. 474). The path of greatest destruction of the tornado may be only a few score yards in width, and its length not more than a few miles, for, after travelling that dis-

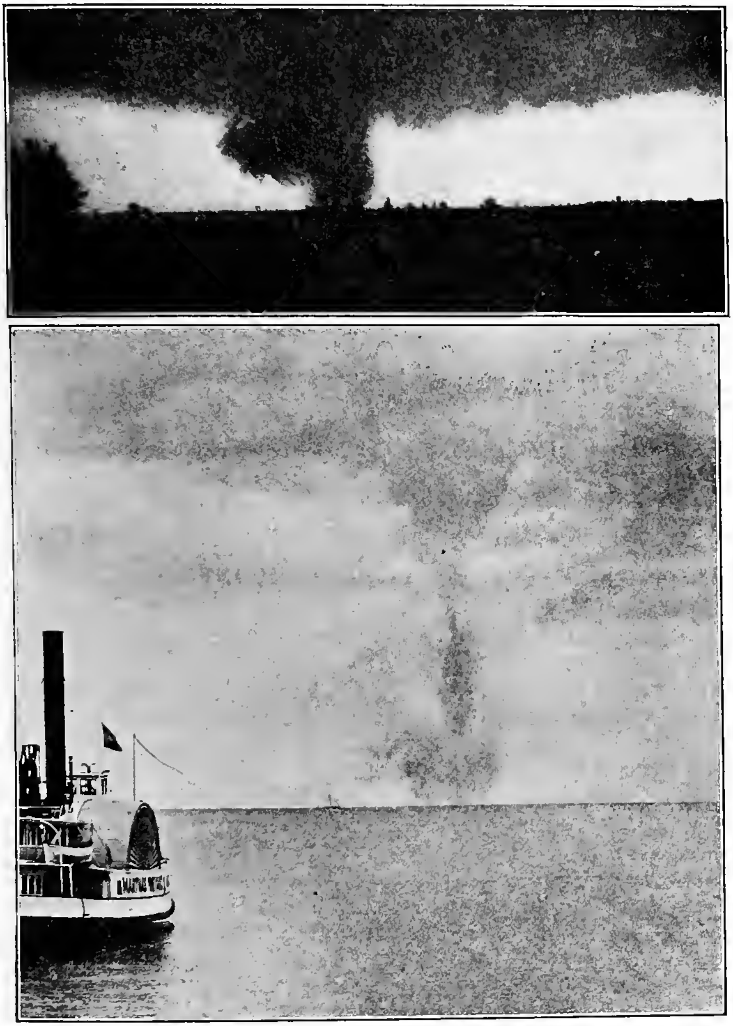


FIG. 476.—Upper view shows a tornado near Mt. Morris, Ill. (W. L. Ikenberry.) Lower view shows a waterspout near Martha's Vineyard, Mass.

tance, the wind may become less violent and the tornado no longer destructive. In spite of the fact that it takes only a minute or two for a tornado to pass, its work of destruction is very complete, and this is one of the most dreaded and destructive forces of nature. In regions of frequent tornadoes it is not uncommon to dig excavations in the ground called " cyclone cellars," in which the people may seek shelter.

Tornadoes are rather abundant in the Mississippi valley (Fig. 475), for there the ground is level and open, and it is easy for the warm, humid air from the Gulf of Mexico to come into close juxtaposition with the cooler upper air from the Great Plains and thus bring about the conditions which favour the formation of a tornado. They are rarely formed east of the Appalachians.

Waterspouts. — When a tornado occurs over the sea or any other body of water, the partial vacuum in the centre allows the water to rise in a low cone, and the spiral winds may actually carry some of the water up in a swirling *waterspout* (Fig. 476). The main part of the waterspout, however, is formed of a hanging cloud, funnel-shaped, as in the tornado.

Hurricanes and Typhoons or Tropical Cyclones

Localization in the Tropics. — A type of storm similar to the cyclones of the belt of prevailing westerly winds is the hurricane, or typhoon, or tropical cyclone. These develop in certain parts of the tropical zone, at certain definite seasons, and move northward or southward into the temperate zone. Such storms are known in the North Atlantic Ocean as *hurricanes* and in the North Pacific as *typhoons*. In the Bay of Bengal, Arabian Sea, and South Indian Ocean the name *cyclone* is commonly used for these storms. The West Indian hurricanes are typical of the group.

West Indian Hurricanes. — The West Indian hurricanes commonly originate in or near the West Indies and pursue a curved path which takes them northwestward toward or into the Gulf of Mexico and then northeastward along the Atlantic coast of the United States. Here they soon become larger and less violent as they pass into the temperate zone. The reason that they recurve eastward may be partly due to the earth's rotation, but is chiefly because of the influence of the prevailing wind. The westward movement of the cyclones is in the trade winds, and the eastward movement is in the prevailing westerlies. Sometimes, however, the West Indian hurricanes continue northwestward to the coast of the Gulf of Mexico and even to the Great Lakes, instead of recurving to the east of Florida.

The West Indian hurricane of September 8, 1900, was accompanied by waves and high water which advanced over the low coast of Texas, submerging a large part of the city of Galveston. This wave and the accompanying violent winds killed 5 or 6 thousand people and destroyed 20 or 30 million dollars' worth of property. The wave was chiefly due to the violence of the storm winds (Figs. 477, 478).

Another destructive West Indian hurricane occurred in 1899, when

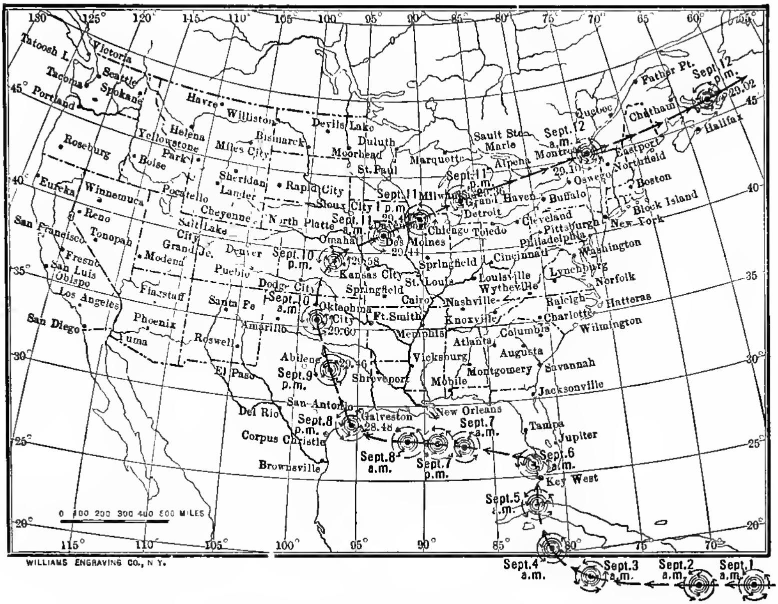


FIG. 477. — The path of the West Indian hurricane which devasted Galveston on Sept. 8, 1900. (After U. S. Weather Bureau.)

FIG. 478. — Wreckage in the city of Galveston, Texas, after the hurricane in 1900.

the centre of the storm traversed the entire length of the island of Porto Rico. Three thousand people lost their lives, most of them being drowned by the storm waves on the coast of Porto Rico, and the winds and heavy rain completely destroyed a coffee crop which would have been worth $7,000,000 if it had matured.

Cause of Tropical Cyclones. — Tropical cyclones are whirls, similar to those of the temperate zones, associated with the rising of warm, humid air in the tropical zone (Fig. 479). They are much larger than tornadoes, but smaller than most extra-tropical cyclones, and originate over the ocean rather than on the land because the humid air over the sea supplies much more vapour. The condensation of this vapour liberates latent heat, which helps to keep up the temperature of the air and causes it to rise still more rapidly. In the centre of a tropical cyclone there is rather low pressure, although it is far from approaching a vacuum. The wind blows violently toward this centre, often having sufficient force to overturn trees and houses. Towns have been devastated and many vessels lost during these severe winds, as at Samoa in 1889, when a number of ships were destroyed during a tropical cyclone. Along the southeastern Atlantic coast of the United States the West Indian hurricanes are often very violent storms, and leave the coast strewn with wreckage. During these hurricanes the rotating storm may only move forward at the rate of 8 to 12 miles an hour, but the wind blowing in toward the centre may have a velocity of 60 to 100 miles an hour. The slow rate of progress and the high wind velocities of the hurricane form a striking contrast with the usually non-destructive cyclonic storm of the temperate zone, which commonly moves eastward at the average rate of 30 miles an hour, while the winds which accompany it rarely have a great velocity. During the hurricane at Galveston in 1900 the anemometer registered a wind velocity of 96 miles an hour and then broke to pieces.

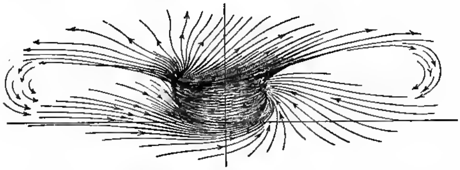


Fig. 479. — Ideal diagram to show movement of air in a hurricane or tropical cyclone. (E. Hayden.)

The time of most frequent occurrence of tropical cyclones in the northern hemisphere is late summer and early fall, because this is when the belt of greatest heat is farthest north. A study of all the West Indian hurricanes from 1876 to 1911 shows that the largest number of hurricanes came during the month of September, — the number begins to increase rapidly during the month of August, and the hurricane season is pretty much over at the end of October (Fig. 480).

Close to the equator no tropical cyclones can occur, because the influence of the earth's rotation (Ferrel's Law, see p. 756) is slight.

Whirls can develop only when the wind is turned to one side so as to start a spiral movement around the centre of rising. These great atmospheric whirls can start only in the hot belt when it has migrated far enough north or south to reach latitudes where the deflective force is sufficient to develop the whirl. It is for this reason that most of the West Indian hurricanes occur in August, September, and October, when the belt of calms is north of the equator.

Hurricane Warnings. — Because of their violence and destructiveness, it is of the greatest importance to issue warnings of the coming of tropical cyclones. With the increase in number of the stations for meteorological observation in the Lesser Antilles and Porto Rico and Cuba, and with additional observations upon vessels reporting regu-

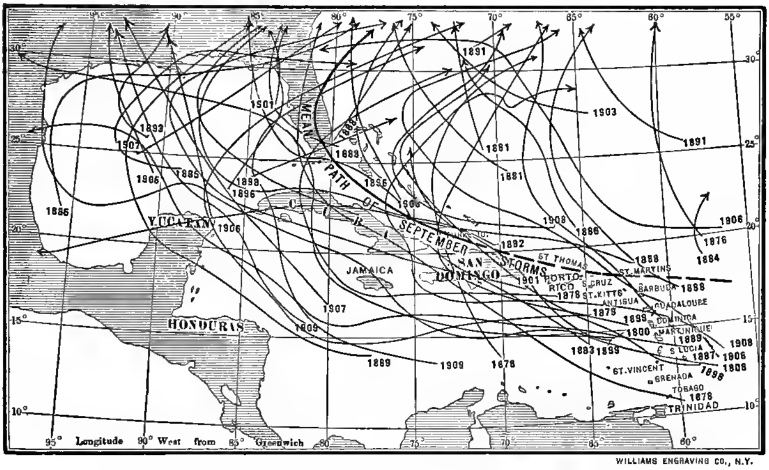


FIG. 480. — The paths of West Indian hurricanes. (Fassig.)

larly by wireless telegraph, the warnings of hurricanes are every year more satisfactory. This is of vast importance in connection with the greatly increased shipping which will traverse the hurricane belt of the Caribbean Sea and the West Indies after the opening of the Panama Canal.

REFERENCES TO LITERATURE

Cleveland Abbe. The Progress of Science as Illustrated by the Development of Meteorology, Smithsonian Report for 1907, No. 1836, pp. 287–309.

W. J. van Bebber. Die Wettervorhersage, Stuttgart, 1898, 219 pp.

Frank H. Bigelow. Storms, Storm Tracks, and Weather Forecasting, Bull. 20, U. S. Weather Bureau, 1897, 87 pp.

A. T. Burrows. The Chinook Winds, Journ. Geog., Vol. 2, 1903, pp. 124–136.

W. M. Davis. The Temperature Zones, Journ. School Geog., Vol. 1, 1897, pp. 139–143.

O. L. Fassig. Hurricanes of the West Indies, Bull. X, U. S. Weather Bureau, Washington, 1913.
William Ferrel. Popular Treatise on the Wind, New York, 1889; Recent Advances in Meteorology, Rept. Chief Signal Officer, Part II, 1885; see also Professional Papers of the Signal Service, No. VIII, 1882, and No. XII, 1882.
J. P. Finley. Tornadoes, New York, 1887.
E. B. Garriott. The West Indian Hurricane of September 1–12, 1900, Nat. Geog. Mag., Vol. 11, 1900, pp. 384–392.
Albert Gockel. Das Gewitter, Köln, 1905, 204 pp.
A. W. Greely. Hurricanes on the Coast of Texas, Nat. Geog. Mag., Vol. 11, 1900, pp. 442–445.
G. Guilbert. Nouvelle Méthode de Prévision du Temps, Paris, 1909, 343 pp.
H. H. Hildebrandsson and Teisserenc de Bort. Les Bases de la Météorologie Dynamique, 2 vols., Paris, 1898, 1907.
Richard Inwards, Weather Lore, London, 1898, 233 pp.
A. McAdie. The Clouds and Fogs of San Francisco, San Francisco, 1912, 106 pp.
W J McGee. The Lessons of Galveston, Nat. Geog. Mag., Vol. 11, 1910, pp. 377–383.
C. F. Marvin. Anemometry, Circular D, Instrument Division, U. S. Weather Bureau, Washington, 1907.
W. L. Moore. Storms and Weather Forecasts, Nat. Geog. Mag., Vol. 8, 1897, pp. 65–82; *ibid.*, Vol. 9. 1898, pp. 255–305.
E. R. Van Cleef. Is There a Type of Storm Path? Monthly Weather Review, Vol. 36, 1908, pp. 56–58.
U. S. Weather Bureau. Pilot Charts; Storm Bulletins, etc.

CHAPTER XXVII

CLIMATE

Weather and Climate

The difference between weather and climate is that *weather* includes the conditions of temperature, pressure, wind, clouds, and rain from day to day, and climate is the average of these weather conditions. We speak of having rainy weather when there is precipitation on several days in succession, but we should not speak of having a rainy climate in a region if it rained on three days in the month and were fair on the remaining twenty-seven. We properly say that certain parts of the tropical zone have a rainy climate. By this we mean that, although the weather on some days is clear, and although it does not rain every day, it is rainy on more days than it is pleasant. The average condition, then, or the *climate,* is rainy.

There is general popular belief that climates are changing at the present time. Accurate meteorological records show that there is no basis whatever for this belief, at least so far as the last century and a half are concerned. There are, however, well-established slight oscillations of climate, of which the 35-year periods of Brückner are best known. There may possibly be shorter periods related in some way to the occurrence of sun spots. There are, of course, climatic variations in the remote geological past, such as (*a*) those cold periods which resulted in the glacial and interglacial oscillations of the Pleistocene (p. 297) and the glacial periods in Southern Africa, India, Australia, and South America in the Permian (p. 299), and in other parts of the earth at still other periods; (*b*) those dry periods when salt and gypsum were formed, as in New York during the Silurian, and (*c*) those moister and perhaps warmer periods when coal was formed in various parts of the earth.

Some of the more important kinds of climate are dry, hot, desert climates; damp, equable, marine, and littoral climates; continental climates; mountain climates; and monsoon climates. The hot, rainy climate is quite characteristic of the equatorial belt of calms, and the extreme or continental climate of interiors of continents.

Climatic Zones

The Five Zones. — The five zones are dependent upon the inclination of the sun's rays, as has already been indicated in connection with the discussion of temperature (p. 725). The distribution of solar heat between the equator and poles results from the different angles at which the sun's rays reach the earth in different latitudes. There has consequently arisen a division of the earth into five climatic zones, — two polar or frigid, two temperate, and one torrid or tropical zone (Fig. 481), or, more properly, two cold zones, two intermediate zones, and one tropical zone.

The boundaries of these zones, as usually outlined, follow the parallels of latitude, but the irregularity of the actual boundaries is indicated in Fig. 481, where the white, which indicates the Arctic or polar zone, is also represented in the temperate and tropical zones, and likewise the conditions of the temperate and tropical zones extend outside their respective boundaries. This is because there are a number of influences which result in an extension of low temperatures into the equatorial region and of high temperatures into the temperate zones.

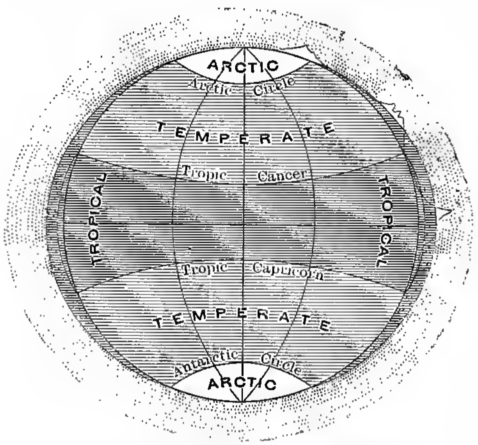


FIG. 481. — Diagram to show how altitude and other features cause the conditions of the polar zones to exist in the tropical zone, etc.

Variation in Zones according to Altitude. — It is well known that the climate of highlands and mountains is cooler, on the average, than that of neighbouring lowlands, and one of the important causes of irregularities in the boundaries of the zones is altitude. On the isothermal charts of the United States (Fig. 482), it is apparent that the isotherms are bent towards the equator in crossing highlands. This is well seen in the mean isothermal chart for July, where the line passing through places having an average July temperature of 70° is diverted southward by the Rocky Mountains, so that instead of running east and west, as it does on the plains, it runs north and south from North Dakota to New Mexico. On the Pacific coast where winds from the equable ocean blow upon the slopes of the north-south mountains the influence of altitude is also apparent, for the isotherms extend north and south instead of east and west. This is because the climate is warm and equable near the coast and the temperature falls as the mountain slopes are ascended so that the climate of the mountain tops is very much cooler.

Variation in Zones under the Influence of Water. — Another cause for modification of climate is distance from the ocean and from other large bodies of water, like the Great Lakes. Islands in the ocean, like Bermuda, have cooler summers and warmer winters than the mainland in the same latitude. Likewise seacoasts, especially on the windward sides of continents, have less extremes of heat and cold

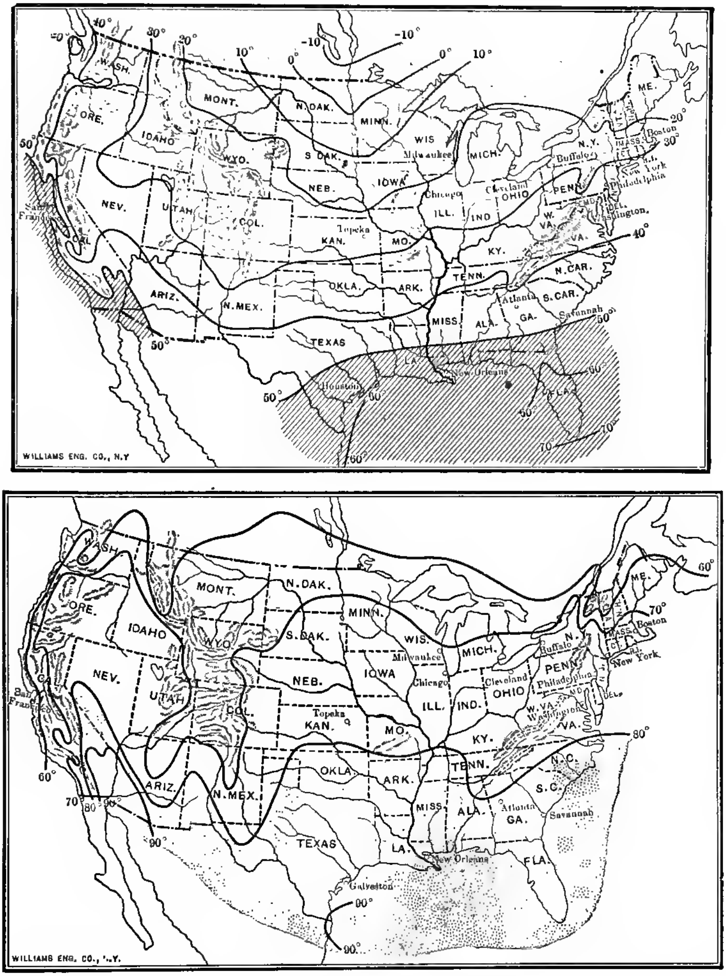


FIG. 482. — Isothermal maps of the United States for January (upper) and for July (lower).

and are said to have a more equable climate than points in the interior of continents. This is well shown in Figs. 428 and 482, where we may compare the temperatures of the state of Washington, Minnesota, and Nova Scotia, which are all in about the same latitude.

In January the region near Puget Sound in Washington has a mean temperature of 30° to 35°, while North Dakota has a mean temperature of from 5° above to 5° below zero, and Nova Scotia has a mean temperature of about 20°. The much higher winter temperatures in Washington and Nova Scotia are due to the fact that these regions are influenced by the ocean, while Minnesota, in the interior of the continent, has much lower temperatures because of its distance from the water.

The isothermal charts of the world furnish many illustrations of the same sort of thing, and there is always a greater range of temperature in the interior of the continent and a smaller range of temperature near the ocean. By mean annual range we mean the difference between the mean temperatures of the warmest and coldest months. If we contrast Asia, the Pacific Ocean, and America, for example (Fig. 497), we find that the mean annual range of temperature is 120° in Siberia, 20° at the Aleutian Islands, and 80° west of Hudson Bay. Likewise in the Atlantic Ocean we find that the mean annual range of temperature for Iceland on the Arctic Circle is exactly the same as that of Mexico on the Tropic of Cancer and of the British Isles halfway between. The mean annual temperature of Iceland is, therefore, very mild for its northerly position, although in this case ocean currents also influence the temperature of this island. In the southern ocean, where there is relatively little land, the mean annual range of temperature is very slight indeed.

Variation in Zones according to Winds. — The best illustration of the variation in zones because of the influence of winds is found where winds blow from water upon land, as in the northwestern United States and Europe (Figs. 428 to 482). The Pacific and Atlantic oceans are warmer in winter and cooler in summer than the continents, and the air over them in the prevailing westerlies is modified accordingly. The eastward movement of this air thus moderates the cold of winter and the heat of summer on the land. Accordingly, agriculture thrives in Norway and Sweden, and large cities are found far north, while the eastern coasts of Labrador and Baffin Land, in the same latitude in eastern North America, are frigid and almost uninhabited. The western coast of North America in the same latitude in Alaska has the equable climate of the British Isles and the Scandinavian Peninsula. London is in the same latitude as southern Labrador, and St. Petersburg is in about the same latitude as southern Greenland. Because of the influence of onshore winds, the temperature at San Francisco in January is the same as that at Charleston, S. C., although the latter is 5° farther south; and the temperature of San Francisco in July is the same as that of Halifax, which is 6° farther north.

The Influence of Ocean Currents. — Just as convectional currents of water in a tea-kettle carry the temperature of the hot surface of the stove to the cooler water at the top of the kettle, so the ocean currents and drifts bear water from the warm tropical zone to the cool temperate and polar zones; and the cold water of the polar zones is carried into the temperate zones by the opposite currents. The temperature of the wind which is blowing over these ocean currents is increased or decreased, and as these winds blow upon the lands they carry with them some of the warmth or the cold which has been brought by the ocean currents from other zones.

In the North Atlantic Ocean this influence of the currents is especially notable (Figs. 416, 428, and 450). The great northward bend of the isotherms west of the British Isles and Scandinavia shows the influence of the warm westerly winds (Fig. 428) in winter, but in summer, when the surface water is warmed by the sun, this influence is less noticeable. The Gulf Stream drift carries part of the isotherms north, and the equatorial return current carries their continuations south. The opposite condition is seen near Newfoundland and Nova Scotia, where the cold Labrador Current bends the isotherms toward the equator and the Gulf Stream crowds them toward our east coast. The isotherms are, therefore, crowded together on the American coast and spread apart in fan-shape on the coast of Europe, resulting in much greater difference of temperature in a short distance in eastern America than in western Europe. There is also similar influence of ocean currents on the isotherms along the west coasts of the United States, South America, and South Africa.

Variation in Zones as a Result of Local Topography. — The eastern part of the state of Washington in the United States has hotter summers and colder winters than the western part of the same state. This is because the Cascade Mountains cut off the winds from the ocean which give an equable climate to the Pacific slope of the state of Washington, but keep it from the eastern part of the state. Throughout the world mountain barriers have a similar influence on the climate of places in their lee. Hills and valleys have slight local effects on climate, chiefly by shutting off winds which may carry warm or cold temperatures.

Other illustrations of the same principle are found in the subtropical climates of Italy, southern Spain, and France. The waters of the Mediterranean are warm, and the Alps, Pyrenees, and other mountains shut off the cold north winds. They also prevent the warm southerly winds from carrying their warmth any great distance away from the Mediterranean. Other factors than topography also influence the mild climate of the Mediterranean countries, but oranges and palms grow in Italy in the latitude of Boston and New York, in the eastern United States. In the latitude of Italy, the eastern United States are visited by killing frosts for several months in the year, and frosts would be fatal to the orange trees of Italy if the protective influence of the Alps on the north did not act as an effective barrier against the incursions of severe cold from the north. Other influences are the lack of a near-by source of severe cold to draw on and the different cyclonic and anticyclonic control to the north.

Resulting Irregularity of the Five Zones. — As a result of the influence of (*a*) altitude, (*b*) water, (*c*) winds, (*d*) ocean currents, and (*e*) local topography, the boundaries of the five zones are exceedingly irregular. Accordingly there have been various suggestions as to different means of drawing the boundaries of the zones. One is that the boundaries between the tropical and temperate zones should follow the limits of the growth of palm trees, and the boundary between the temperate and polar zones should follow the limits of the growth of wheat. Another suggestion is that (*a*) the annual isotherms

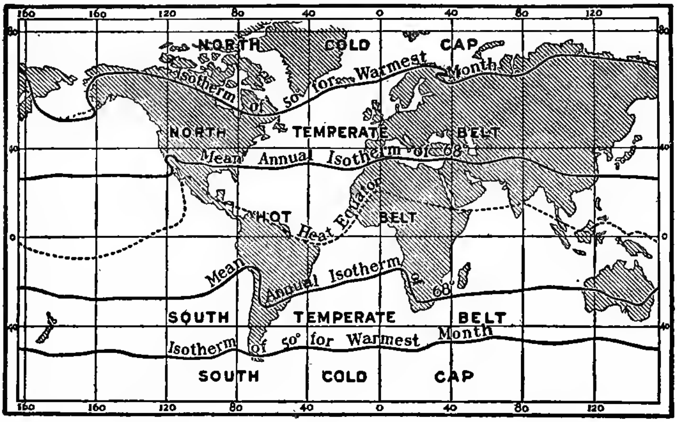


FIG. 483. — Supan's suggestion as to zones. (After Ward.)

of 68° F., and (*b*) the temperature of 50° F. for the warmest month, should delimit the zones (Fig. 483). It has also been suggested that the temperate and tropical zones should be separated, not by the Tropics of Cancer and Capricorn, but by the northern and southern boundaries of the trade wind belts. None of these substitutes is a sufficient improvement to be generally adopted, and the boundaries which follow the tropics and Arctic and Antarctic circles are generally used.

Climate of the Belt of Equatorial Calms

The Hot, Rainy Belt. — The conditions of temperature, humidity and rainfall, and the absence of regular winds give the belt of calms a distinctive climate. They have a notable influence on life there. The climate of the belt of calms, however, is not characteristic of the whole tropical zone, and in the following pages it will be seen that the climates of the world are best described in relation to the atmospheric circulation rather than the zones of heat.

The climate of the doldrums (Fig. 484) is hot because of the great absorption of heat by the earth under the direct rays of the sun at the times when they are vertical, and the consequent heating of the air through radiation, conduction, and convection. The air contains a great deal of moisture, and, as it rises, the water vapour is condensed into rain as soon as a sufficient elevation is reached. The belt of calms, therefore, has a very rainy climate (Fig. 485).

One striking characteristic of the climate of the doldrum belt is its monotonous uniformity. The heat increases rapidly after sunrise, and clouds soon form. In the afternoon these often develop into violent thunderstorms, from which heavy rain falls. Radiation during the night is not sufficient to cool the humid air much. Because of the upward movement of the air there is an absence of steady wind during both night and day, and sailing vessels are often becalmed for days at a time. These conditions are repeated regularly. On the land the temperatures during the day are higher than over the water, and sea-breezes sometimes blow along the coast because of the differences of temperature there.

Many parts of the doldrum belt may be spoken of as having a single hot rainy season. Some parts of it, however, because of the shifting of the heat equator, may be said to have two rainy seasons and two less rainy seasons.

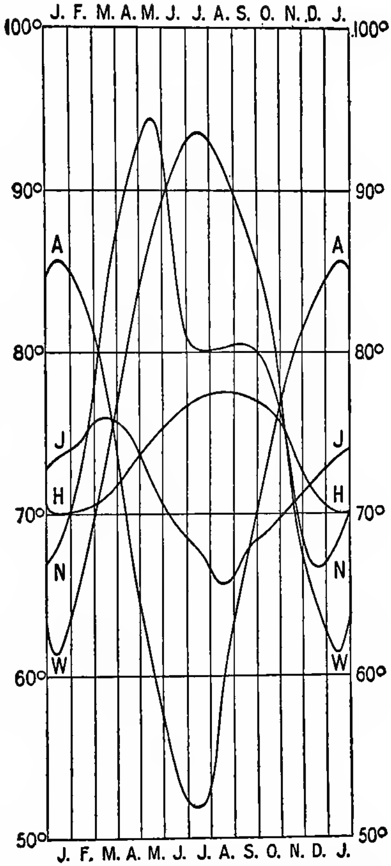


Fig. 484. — Seasonal range of temperature in the tropics. (Ward.) W — Wadi Halfa; N — Nagpur; A — Alice Springs; H — Honolulu; J — Jamestown, St. Helena.

Backwardness of Inhabitants. — Because of the heavy rainfall and the warmth, which permits trees to grow throughout the year, there are dense forests on the land. Within these forests the air is reeking with moisture. The climate is so warm and damp that it is difficult to work. It is so hard to clear away the vegetation that the task is not readily undertaken.

This is especially true because the forest plants themselves yield abundant food with little labour. On this account the people who live in the tropical forest of the belt of equatorial calms are apt to depend directly upon nature for their food; and most of the inhabitants of the equatorial region have made little progress toward civilization because they have little ambition for improving their condition.

Climate of the Trade Wind Belts

Rainy Windward Coasts. — In the trade wind belt there is a difference between (*a*) rising coasts which face the direction from which the trade winds come, (*b*) the lowland areas, and (*c*) the lee coasts.

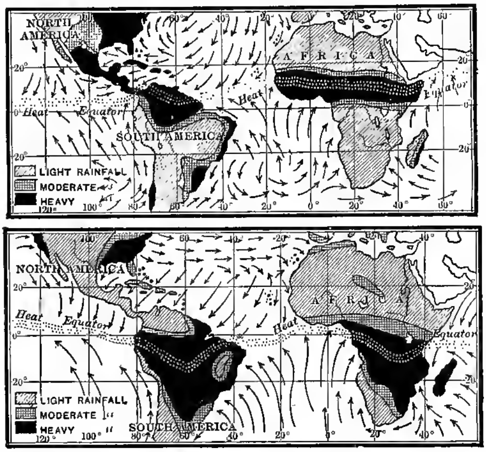


Fig. 485. — Contrast of summer (upper) and winter (lower) as to distribution of tropical rainfall in relation to the shifting of the heat equator (stippled).

In the regions north and south of the belt of calms the trade winds are blowing towards a warmer region. They are, therefore, constantly evaporating water from the surface of the ocean and from streams and lakes on the land, because the warmer the air becomes, the more vapour it can contain. Indeed, so much fresh water is removed from the surface of the sea in the trade wind belts that the sea water becomes more saline in these regions. When the trade winds blow over rising land, the coast which faces them causes the air to rise. It is, therefore, cooled and has its vapour condensed as abundant rainfall. This is well shown on the eastern side of the Isthmus of Panama and the northeastern coast of Brazil (Fig. 486), which receive a heavy rainfall from the northeast trades. Likewise the southeastern coast of Brazil receives heavy rainfall from the southeast trades. East-facing coasts throughout the world in the trade wind belts are therefore usually rainy. Parts of the East and West Indies (Fig. 486), northeastern Australia (Fig. 488), and southeastern Africa (Fig. 487) likewise have heavy rains because the trade winds blow upon them from the sea. These places also have a tropical forest, resembling that of the belt of calms. The Hawaiian Islands in the Pacific Ocean have heavy rains on the eastern side and a dry climate on the opposite side. This is because they lie in the belt of northeast trades, and the same thing

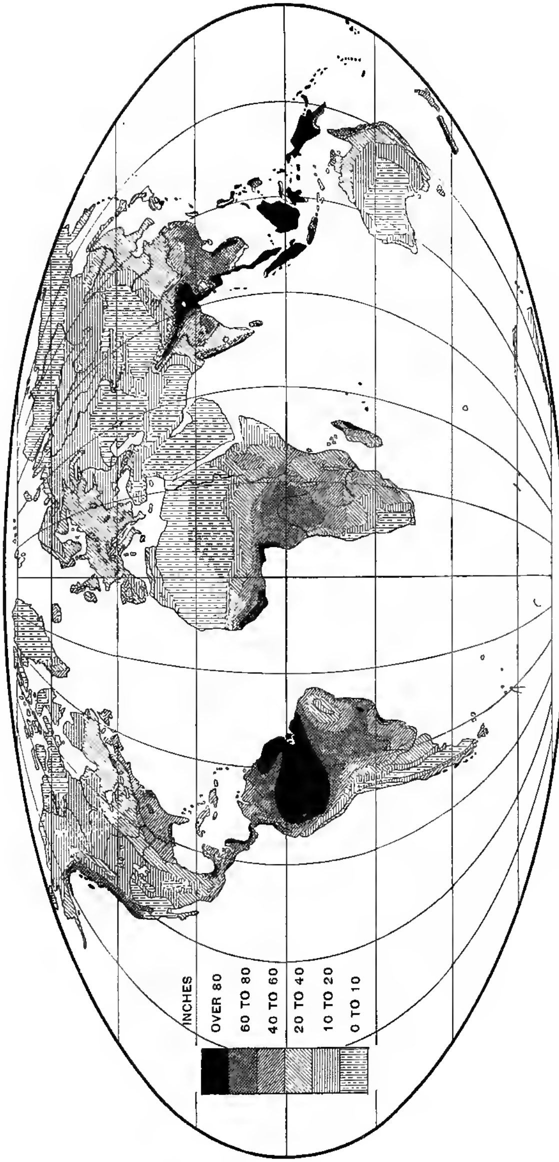


FIG. 486. — Rainfall map of the world. (Herbertson and Taylor.)

is characteristic of all mountainous islands in either of the trade wind belts.

Desert Trade Wind Belts. — The largest and best known desert in the world is the Sahara in northern Africa. The cause of the Sahara is the blowing of the northeast trades across northern Africa. Throughout the other portions of the trade wind belts of the world, on land, conditions of aridity are far more common than rainy climates, and in fact the trade winds are the most important cause of deserts.

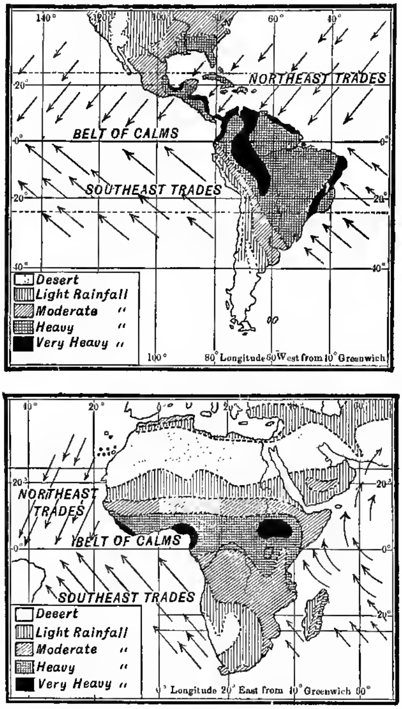


Fig. 487. — The desert trade wind belts in South America and Africa.

The trade winds are ready to take up vapour in passing over the land, as they are in passing over the ocean, because the air is moving towards the warmer equatorial region and having its capacity for moisture increased. In contrast with the trade winds on the ocean, however, those on the land can obtain so little moisture that they become very dry winds, with vapour rising into them wherever there is water to evaporate. This leaves so little water for plants that the land becomes a desert. It should not be thought, however, that it never rains in the Sahara, for the occasional mountains and hills there cause the trade winds to rise and precipitate moisture on the windward slopes. Thus rain sometimes falls in parts of the Sahara. The water is quickly evaporated, however, and rivers which flow down the desert slopes of the mountains wither a short distance from the base. Most of the Sahara has less than 10 inches of rainfall per year, and the Mohave desert of Arizona has a rainfall of less than 2 inches a year.

These conditions cause a broad belt of arid and desert country both north and south of the equator. It extends completely across each of the continents in the trade wind belts, except on the east-facing coasts where the trade winds bring rain and the eastern slopes of mountains in the interiors of the continents. Such deserts are found in Australia (Fig. 488), South Africa (Fig. 490), South America (Fig. 487), and southwestern United States (Fig. 496) and Mexico. The largest desert tract is in northern Africa and southwestern Asia. From the Atlantic Ocean near the Cape Verde Islands a series of deserts extend eastward through Africa, Arabia, Persia, and southwestern Asia. The great Sahara is a part of this belt.

In these deserts life is very different from that in the tropical forest. There are not many species of plants capable of adapting themselves to life among such unfavourable conditions, and even these are scattered. The desert is, therefore, a barren open country avoided by animals and by man and, consequently, among the most sparsely settled parts of the world (Fig. 489).

Desert weather is nearly always dry, the sky is usually cloudless, and the prevalent winds often blow the sand about and even cause dangerous sand storms. In the temperate zone deserts, the days may not always be as warm as in the tropical zone, but even in the temperate zone they become very hot indeed. The desert of southern Arizona, although far north of the Tropic of Cancer, is sometimes so warm that the thermometer rises to about 100° or 120° in the shade. The highest air temperature ever "officially" recorded, said to be 154° F., was in northern Africa in the central Sahara. Because of the lack of moisture in the air, radiation proceeds with great rapidity after the sun has set and the ground and the air cool so quickly that it is often necessary to keep covered with blankets at night in places where, during the day, it may become insufferably hot.

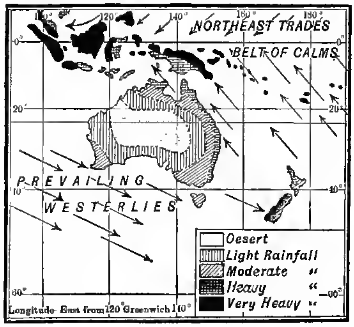


FIG. 488. — The desert trade wind belt in Australia.

Oases in Deserts. — Any area in a desert where water may be obtained is spoken of as an *oasis*. Oases are usually either scattered springs or places where streams descend from mountains and flow out upon alluvial fans. The typical oasis at a spring is illustrated by the number of isolated oases of this character in the Sahara, while the oasis upon a river is well seen at such cities as Merv and Bokhara, southeast of the Caspian Sea. Another type of oasis is represented by the narrow strip of country along the Nile in Egypt, with the Libyan and Nubian deserts on either side. These two deserts are really parts of the Sahara, and the oasis of the Nile is made possible by the water which flows across the desert to the Mediterranean.

The importance of the oases is, of course, the opportunity to obtain water for men and animals as they travel across the desert, or to maintain permanent homes in places where there is a water supply. In some respects oases seem to excel humid regions, probably because in places where water is obtainable the hot climate makes it possible to raise many crops each year. In any event, the large oases of the Nile and Euphrates rivers supported civilization long before there were civilized people in any part of Europe, and, at the oases in the southwestern part of the United States, the Pueblo Indians developed a civilization far ahead of that of the aboriginal inhabitants of the rest of this country. The small oases, surrounding a single spring and with the date palm as the chief sort of vegetation, support a small

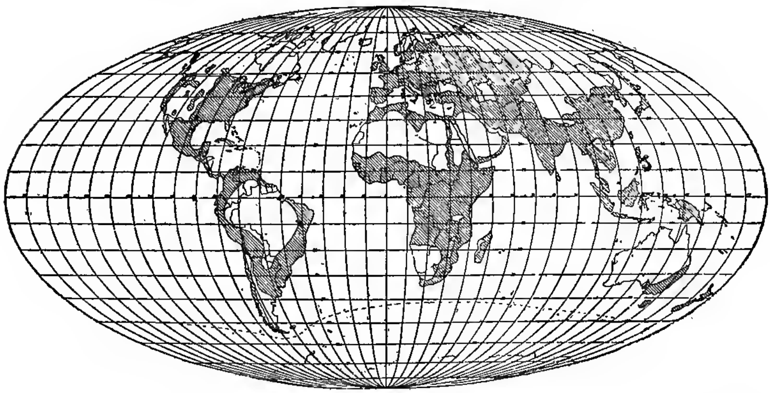


FIG. 489. — The world's belts of sparce population. The lined areas show the regions which had an average of over $2\frac{1}{2}$ persons to the square mile in 1905. White areas with less population are: (*a*) dry, as in Sahara, western United States, etc.; (*b*) cold, as in Siberia, northern Canada, etc.; or (*c*) too hot and damp, as in part of Brazil. (Jefferson.)

permanent population, as well as furnishing stopping places for caravans which must obtain water as they cross the desert.

Dry Lee Coasts. — The dry climate of the leeward sides of continents and islands in the trade wind belts is the result of the fact that the wind does not blow from the ocean. This is the case on the western side of the Hawaiian Islands, on the west coast of Mexico, and the west coast of South Africa. The trade wind is there blowing off the land, and is dry.

SAVANNA BELTS

Wet and Dry Seasons. — The savanna belts are located between the rainy belt of calms and the trade wind deserts, where the lands in each hemisphere have a region with alternate dry and wet seasons. This climate is due to the migration of the heat equator and the shifting of the borders of the belts of calms and the trade winds. The belt of calms moves northward in the hot season and the savannas of the northern hemisphere then have heavy rain (Figs. 485 and 490). The belt of calms migrates back toward the equator, and these savannas then come under the influence of the dry trade winds. In the southern hemisphere the savannas similarly have their rainy season in their summer, when the doldrums are south of the equator.

Plants and Animals of the Savannas. — The absence of trees in the savannas and the great abundance of grass marks them as gradation areas between the belt of calms with its heavy forest and the arid portions of the trade wind belts, with their sparse vegetation. During the rainy season the savannas have copious rainfall, and vegetation springs up and grows rapidly, but during the dry season the vegetation withers because the ground is parched by evaporation. The absence of trees is due to the severity of the drought, and the presence of grass is the result of the fact that the grass grows rapidly during the wet season and is able to survive a period of drought.

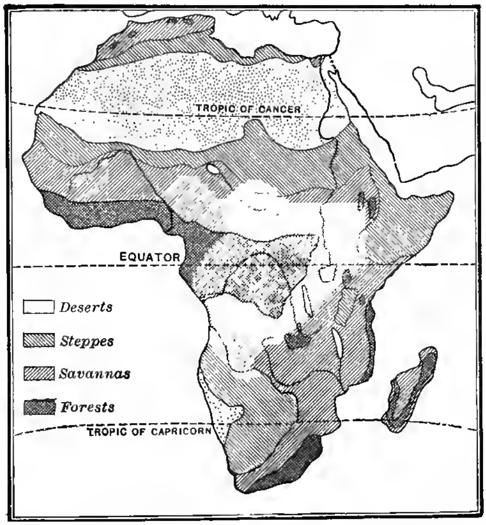


Fig. 490. — The distribution of the savannas in Africa. Forested belts along rivers interrupt the general grassy condition.

The name *savannas* is not the only one applied to the savanna belts, the name *llanos* being used in Venezuela and Columbia, *campos* in Brazil, *downs* in Australia, and *park lands* in Africa. In contrast with the absence of animal life in the desert, the savannas support great numbers of plant-eating animals and flesh-eating mammals which prey upon them.

The Future of the Savannas. — There is no doubt that the savannas are destined to be the most productive and populous lands in the tropics. Agriculture is favoured by the absence of forest, and the seasonal drought makes it necessary to provide for that season, just as we must provide for the cold winter in the temperate zone. The inhabitants of the savannas are, therefore, forced to be industrious and thrifty; and in Africa the negroes of the savanna belts raise crops and cattle and are the most civilized natives on the continent.

Monsoon Climates

The influence of the monsoon winds in India produces a climate with three well-defined seasons, — (*a*) the hot season, (*b*) the rains, and (*c*) the cool winter. Southeastern Asia and most other monsoon countries have only two seasons, one cold or cool and dry, the other damp and warm.

The Hot Season in India. — The hot season of India lasts from April to June. At that time the hot, dry air of the northeast monsoon, blowing over the land, may cause the temperature to rise above 100° in the shade. Toward the end of the hot season in June, the northeast monsoon ceases to blow, because the temperatures of the land and ocean are approaching equality and the barometric gradient is annulled. A calm therefore ensues, and at this time the heat is almost suffocating (Fig. 491).

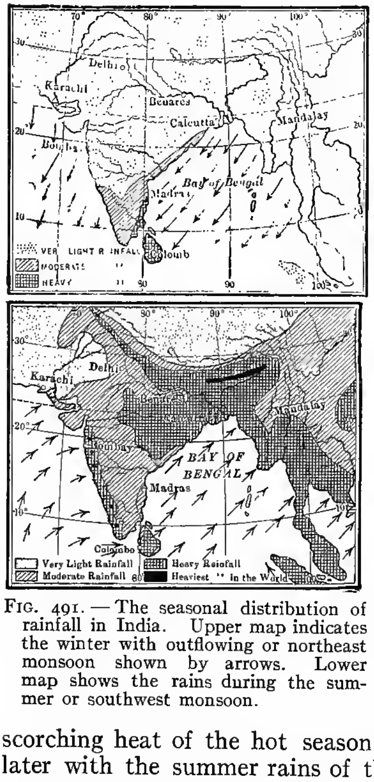


FIG. 491. — The seasonal distribution of rainfall in India. Upper map indicates the winter with outflowing or northeast monsoon shown by arrows. Lower map shows the rains during the summer or southwest monsoon.

The Rains. — The season known as *the rains* is the time of the summer monsoon, when the southwest monsoon blows from the Indian Ocean to the land. Clouds appear, rain falls almost every day, and for a few weeks vegetation flourishes. A short period of calm follows the summer monsoon.

The Winter. — The winter is the time of the northeast monsoon, and the heat in the preceding period of calms is relieved by the flowing of cool air from the interior toward the sea. The winter monsoon becomes established early in October, and the air is then clear and cool, except during the period of winter rains in northern India. By January it is necessary to heat houses with fires in many parts of India. A sort of spring follows this winter during February and March, and vegetation may spring up, but it is soon withered by the scorching heat of the hot season. The real growing season comes later with the summer rains of the southwest monsoon.

The Heaviest Rainfall in the World. — The rainfall on the mountain slopes of India at the base of the Himalayas is the heaviest in the world. At some points there is a rainfall of somewhat less than 500 inches, that is, an amount which would form a layer 40 feet deep if it remained where it fell. Of this amount about two-thirds comes during the five summer months; and on a single day there may be as much as 40 inches of rain, or more than falls in many parts of the United States in a year. Indeed, this rainfall is so heavy that on some of the mountain slopes in India the soil is completely removed by stream erosion.

The Climates of Intermediate or Temperate Zones

Intermediate Zones. — The so-called temperate zones are far from temperate in their climatic character, and it is much better to speak of them as the intermediate zones. The differences from north to south occur chiefly in connection with (*a*) temperature, (*b*) rainfall.

Variation from North to South. — Because of the varying inclination of the sun's rays there is a notable increase in the warmth of the intermediate zones from the polar to the tropic regions (Fig. 492). Near the tropics, however, there is no very decided difference between the temperature of summer and winter; but away from the tropics the summer and winter temperatures are so different that the year is naturally divided into four seasons of spring, summer, autumn, and winter. In the vicinity of the Arctic and Antarctic circles the winters are so extremely cold and the summers are so cool that the climate may be spoken of as subarctic.

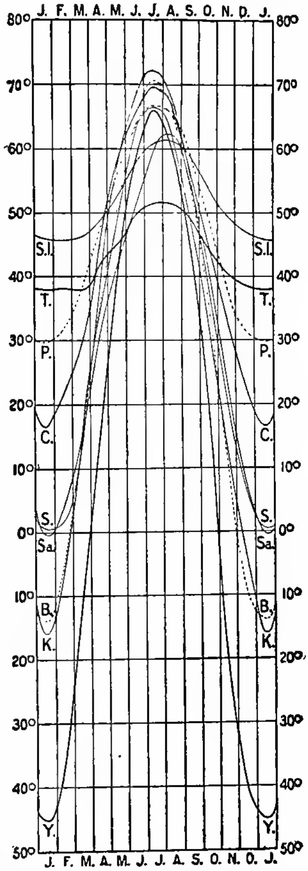


Fig. 492. — Seasonal range of temperature in the intermediate or temperate zones. (Ward.) S. I. — Scilly Isles; P. — Prague; C. — Charcow; S. — Semipalatinsk; K. — Kiakhta; B. — Blagoweshtchensk; Sa. — Sakhalin; T. — Thorshavn; Y. — Yakutsk.

The subarctic portions of the intermediate zones have few trees and, at the extreme limits, no trees whatever. Where there are few trees, they are stunted individuals, and in the region near Hudson Bay, for example, there may be full-grown trees which are only 2 or 3 feet in height. In certain of the lands near the polar circles, no agriculture is possible; and there are scarcely any human inhabitants except where mining camps, such as those of Alaska and the Klondike, or fishing towns along the seacoast, like some in Norway and Siberia, result in small centres of population.

With the increase of temperature toward the tropics there is a change of vegetation. This is well illustrated in North America. There the treeless tundra of the north merges southward into a forest belt, and vegetation becomes more and more luxuriant in southern

Canada and in the United States, so that the grains and temperate zone fruits are raised. In southern United States near the tropics the climate is so warm that it may be spoken of as subtropical. In this warm belt the plants useful to man produce cotton, sugar, oranges, and, near the warm ocean, bananas, pineapples, and cocoanuts.

The differences in rainfall between the equatorial and the polar margins of the intermediate or temperate zones are related to the temperature as well. There is moderate rainfall throughout most of the temperate zones, but it decreases toward the polar zone because cool air has less capacity for vapour than warm air. The rainfall also decreases towards the tropics, because of the lessened capacity for moisture in the descending air of the arid horse latitude belts.

Steppes. — Such regions as Spain, Italy, and Greece in Europe, and southern California in the United States, are in the horse latitude or subtropical belt. They grade on the one hand into the desert trade wind belts and on the other into the moist climate of the mid-temperate zone and may be called the *belts of steppes*. Not all of the horse latitude belts are arid, however, Florida, for example, having abundant rainfall because it projects into the Gulf of Mexico and the Atlantic Ocean, and has nearly all its winds blowing from over the water. Some parts of the horse latitudes, however, are true desert.

Steppes are similar to savannas in having a limitation of plant growth because of the climate. The borders of the horse latitude belts have a migration of wind and of climatic conditions, some portions being reached by the prevailing westerlies when they shift southward in the winter of the northern hemisphere, bringing with them snow and rain. The converse applies in the southern hemisphere. The steppes are dry in summer, however, when they are in the belt of the descending air of the horse latitudes, or the northern edge of the drying trade winds. On this account it is necessary to practise irrigation in order to carry on agriculture, chiefly because the regions of steppes are apt to have their rainfall in the wrong season of the year. Italy, by way of illustration, has rainy winters and dry summers. Therefore the Italian farmers irrigate their crops, which are growing in summer at the time when the moisture is deficient. Steppes are usually too dry for trees, but grass grows upon them and the curing of this grass to natural hay during the warm, dry summer makes good ranges for cattle. The Great Plains in Texas furnish an illustration of steppes with a grazing industry.

Variation from West to East. — There are likewise variations in the climate of the intermediate or temperate zones from west to east. These are also dependent on (*a*) temperature, and (*b*) rainfall, being directly determined by the fact that the prevailing winds of the intermediate zones are from the west. These variations are best considered by a discussion of (*a*) west coasts, (*b*) regions near meridional mountains, (*c*) the interiors of continents, and (*d*) east coasts.

West Coasts. — The west coast of the United States, from northern California to Puget Sound, and the northwest coast of Europe have a humid, equable climate because of the warm damp winds which blow from the ocean against these west-facing coasts (Fig. 493). Ireland, on the northwest coast of Europe, for example, is known as the Emerald Isle, because the damp air keeps the grass always green. It never has droughts, during which the grass is parched and turns brown, as in the eastern part of the United States.

The heaviest rainfall in the United States is in the western parts of Washington and Oregon, and, in certain places, amounts to more than 100 inches a year. This is because the vapour in the damp air from the ocean is precipitated during the rising of the prevailing westerlies over the mountain slope. The winter of cities like Seattle and Portland is not a cold season, as in eastern and central United States, but rather a damp and cool season. This is because the prevailing westerlies are strongest in winter and because there are more storms then. There is practically no precipitation in the form of snow because of the warm temperature near the ocean. There is heavy rainfall on the southwestern coast of Chile for the same reasons. Northern Chile and southern California, however, have an arid climate, even on the seacoast, because they are not well within the belt of the prevailing westerlies, and therefore have the characteristic conditions of the horse latitudes and trade wind belts. The coast of Norway and the British Isles has a prevalence of rain and cloudy weather during the winter, similar to that in Washington, Oregon, and southern Chile.

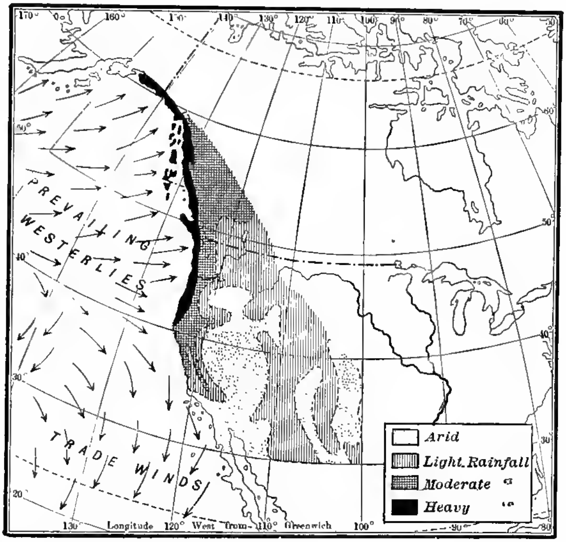


Fig. 493. — The heavy rainfall of the west coast of North America in the region of prevailing westerlies.

Regions near Meridional Mountains. — The heavy rainfall of eastern Norway, Scotland, Wales, and Ireland is not limited by the mountain crests, as is the case in Washington, Oregon, and Chile. This is because these American mountains are much more lofty and are continuous, while the highlands of western Europe are low and broken. Accordingly the winds on the west coast of Europe are able to carry vapour far inland and even across the plains of Russia into western Asia. Europe, therefore, is well watered, since most of it lies north of the horse latitude belt. It contains no desert and, except on the plateau of Spain and near the shores of the Caspian, no arid region (Fig. 494). This explains the extensive agriculture of Europe.

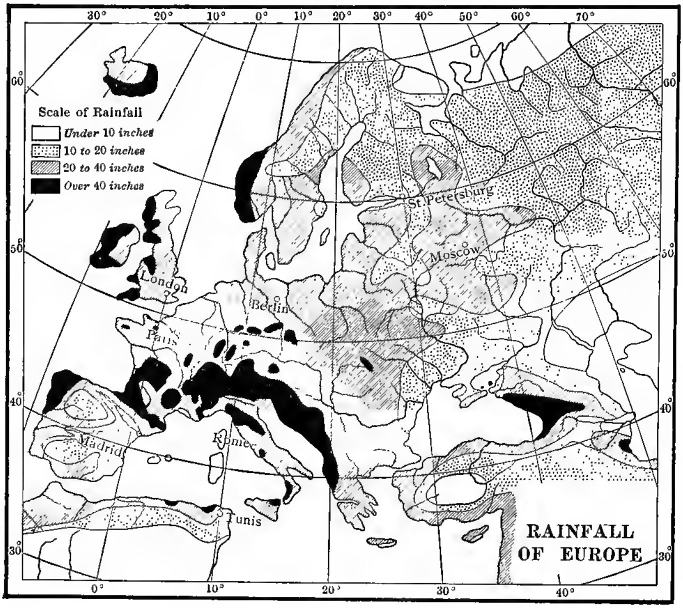


FIG. 494. — Rainfall map of Europe.

The western part of North America forms a decided contrast, because the lofty, continuous Cascade and Sierra Nevada ranges prevent the wind from carrying vapour far inland, and so much vapour is condensed on the western slopes that the winds descend the eastern slopes as dry winds. It therefore happens that from the Sierra Nevada and Cascade ranges eastward to the 100th meridian most of the United States is arid or semi-arid (Fig. 495). Although the Mississippi valley is the part of North America which corresponds in position to well-watered Germany, Austria, and eastern Russia in Europe, destructive droughts frequently take place there. Within the arid belt to the west, however, there are local mountain ranges like the Rockies and Black Hills which have greater precipitation than the intervening plains and plateaus (Fig. 496).

Interiors of Continents. — Because of distance from the sea, the interiors of continents usually have less rainfall than the coasts. This is the cause of frequent droughts in central and western Asia and in the central United States. In the northern United States and southern Canada these droughts are less destructive than they are to the south, because light rainfall will support crops in a cool climate.

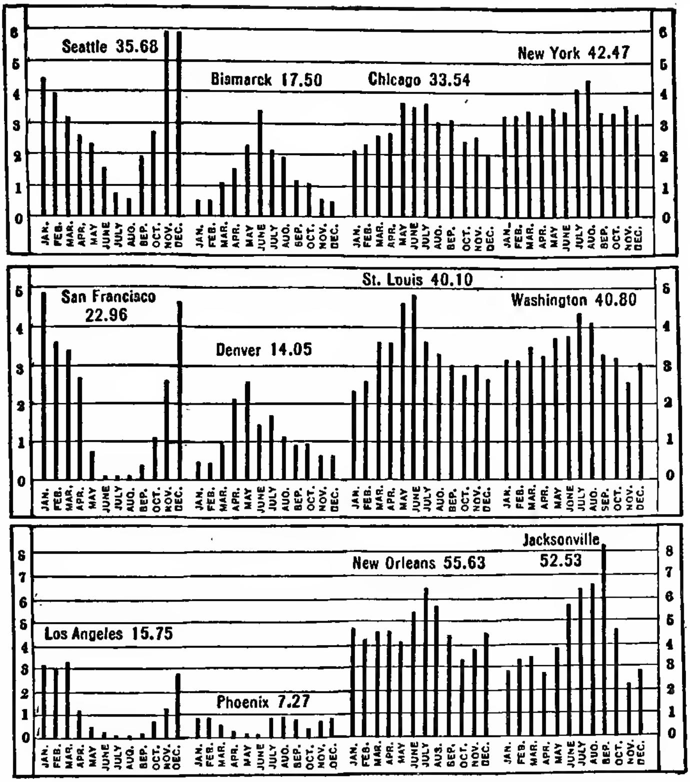


FIG. 495. — Monthly precipitation at selected stations in United States, showing variations from west to east and north to south. (After Milham.)

Two factors enter into this: first, the smaller evaporation of the cool regions allows the dampness to remain in the ground for a longer time; and, secondly, the melting of the frozen soil keeps the soil damp late into the summer.

East Coasts. — Although windward coasts are rainy, and leeward coasts are dry, in the trade wind belt, it does not necessarily follow that because the west-facing or windward coasts of the prevailing westerlies are rainy, that the east-facing or leeward coasts of the prevailing westerlies should be dry. The air in the prevailing westerlies has crossed the whole continent before coming to the east coast and has obtained little moisture on the way except such as might be evaporated from lakes and rivers. What prevents aridity on east coasts, however, is the cyclonic storm eddies of the prevailing westerly wind belt. It will be recalled that in the prevailing westerlies the winds of these storms blow in from all sides toward the centre of low pressure. Consequently some of the winds of eastern and southeastern United States blow from the Atlantic Ocean and Gulf of Mexico. These winds bring abundant rainfall to the eastern United States, and the annual

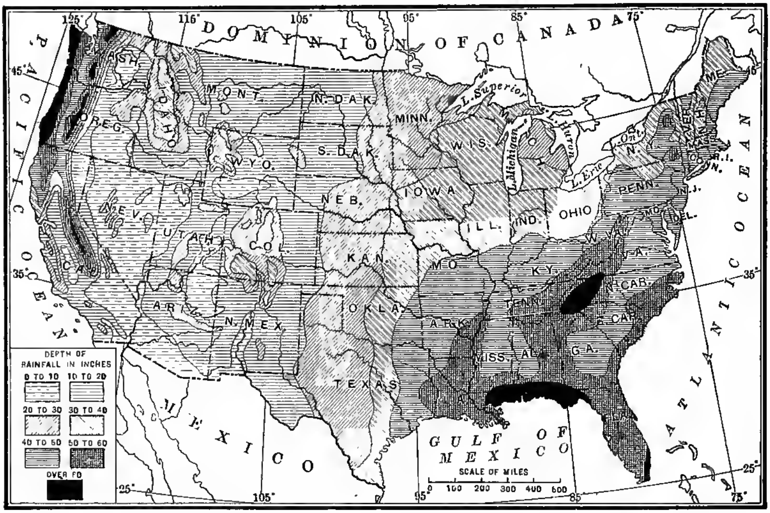


FIG. 496. — Rainfall map of the United States. (Gannett.)

precipitation of parts of North Carolina, Tennessee, Florida, and the Gulf States (Fig. 496) is over 60 inches.

East coasts have changeable weather on account of the influence of these cyclonic storms. In summer the northwest winds are dry and cool, in winter dry and cold. Whenever storm winds blow from the sea, the temperature and humidity are modified by the waters of the ocean. Thus the south winds are warmed in passing over the Gulf Stream or the Gulf of Mexico and carry warmth and dampness to the southern and eastern states. The east winds are cooled in the summer in blowing over the Labrador Current, and are damp and chilly, often bringing fogs to Nova Scotia and the New England states. Because of the influence of winds, the east coasts may have weather which during one day is like that of the interior of the continent and on the next like that of the equable ocean. The northeastern coast of China has a climate similar to that of the eastern United States, being characterized by the seasonal contrasts which are typical of the eastern coasts in the temperate zones.

Variation from Seacoast to Interior. — The variation in the climate of the temperate zones from seacoasts to the interior has been illustrated by the contrasts of the west coast, interior, and east coast, but there is also a notable contrast between the seacoast with its more or less *equable* climate and the interior of the continent with what we call a *continental* climate, characterized by great extremes.

Throughout the world we find that in the intermediate or temperate zones there is a considerable difference between (*a*) the interior of the

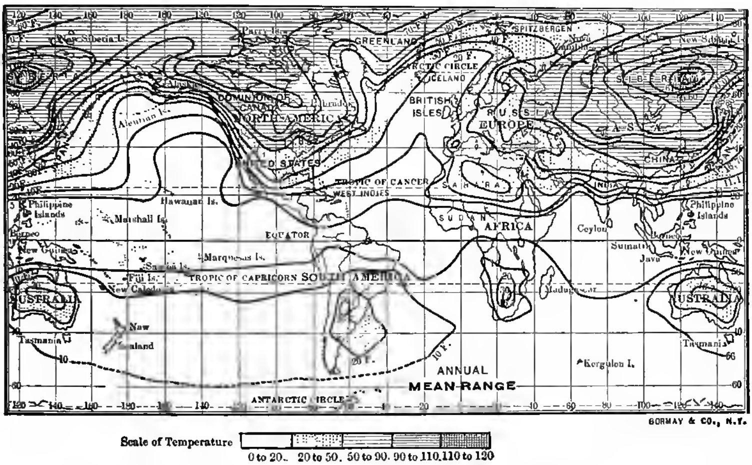


FIG. 497. — Map showing mean annual range of temperature for the world. (Bartholomew.)

continent, which has warm or hot summers and cool or cold winters, and (*b*) the seacoast, where the summers may not be oppressively hot and the winters not unbearably cold. During a summer day in middle latitudes of the intermediate zones the temperature in the interior of a continent may arise above 100°, and in winter it may descend as much as 40° below zero. This is an extreme range of 140° in a year, and the summer has the climate of the tropical zone, and the winter tends toward the climate of a polar region. In United States, Minnesota and the Dakotas have this extreme or continental climate. The same thing is found in north central Siberia near the Arctic Circle, where hot summers are followed by bitterly cold winters. This latter is the coldest part of the world in winter and is sometimes spoken of as a *cold pole* of the earth (Fig. 497).

The extreme climate of the interior of a continent is chiefly due to distance from the sea and freedom from its influence. In summer, the land warms because the sun stays a long time above the horizon, even though in the temperate zones it is not very high in the heavens except on the tropics, where it is overhead at noon on the summer solstice. In the winter the nights are very long and the sun is much lower in the heavens than during the summer. This results in such extreme radiation that the land loses the excessive heat which it has accumulated during the summer and becomes exceedingly cold.

Certain seacoast regions are said to have an equable climate because they are generally characterized by lack of extremes, though this is not true of all coastal regions, the northeastern parts of United States and China furnishing exceptions. Equability is likewise due to the influence of the ocean, which may be thought of as a stubborn medium, gaining heat more slowly than the land in summer and losing it more slowly than the land in winter. In summer or winter the winds carry the temperature of the ocean to the parts of the continents away from the sea, which have an equable climate throughout the year because the heat of summer and the cold of winter are ameliorated by the winds from the ocean.

Climate of the United States. — The contrast of climates of the east and west coasts and of seacoasts and interiors is all well illustrated in the United States. We may speak of the climate of the west coast as equable, the western part of the interior as continental, the eastern interior and the east coast as somewhat-modified continental, and the southeast coast as equable. Eastern United States, meaning the region from the Great Plains and Mississippi valley to the Atlantic Ocean, is so important to a majority of users of this book that it seems profitable to consider its weather and climate in slightly greater detail.

Summer Weather in Eastern United States. — The following is an actual illustration of typical summer weather in eastern United States. An anticyclone is passing over the region. The day is one of agreeable warmth, with a cool, dry, gentle west wind and a nearly cloudless sky. The following night is one of refreshing coolness.

The anticyclone is followed by an area of moderately low pressure. With the approach of this Low the wind shifts from west to southeast, the temperature increases, the air becomes more humid, and both day and night are muggy and oppressive.

The second day begins with the sky flecked by small clouds, which in the afternoon grow to thunder-heads. These may give rise to a thundershower in the afternoon. Just before the thundershower there is a sharp wind squall, and during the shower there is heavy rain and severe lightning and thunder (Fig. 498).

As soon as the storm is over, the wind shifts to the west again, because another anticyclone has followed the Low. With the passage of this second anticylone the air is again dry and refreshing.

Summer weather in the United States is commonly a succession of just such days as are described above, the cycle being repeated with regularity (Figs. 459, 499), although there are slight variations. For

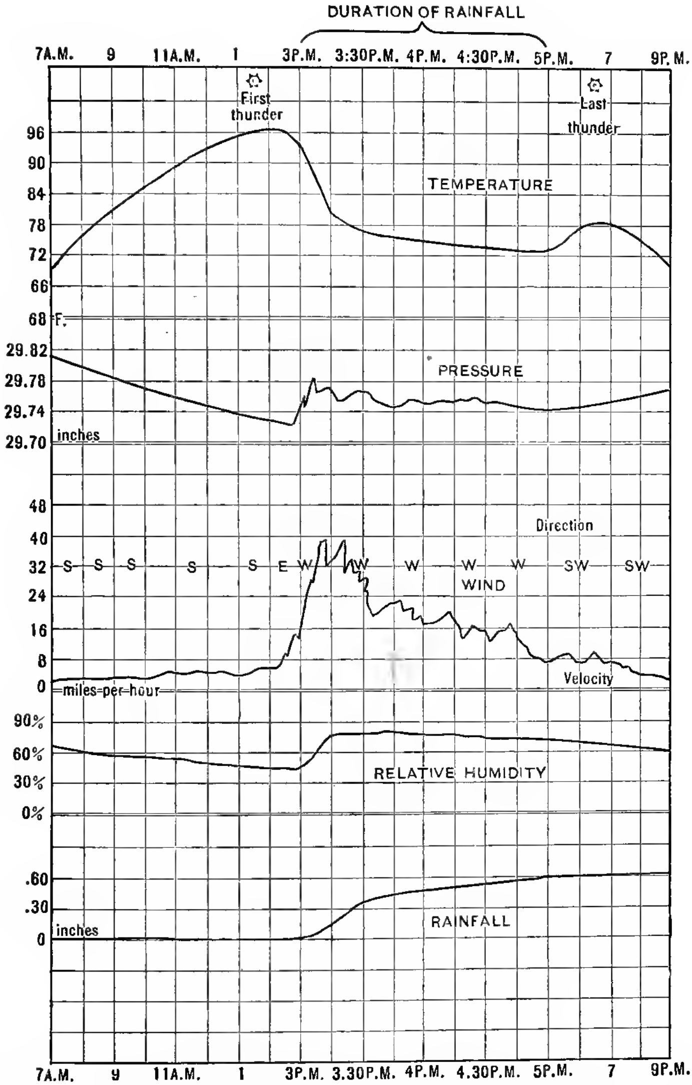
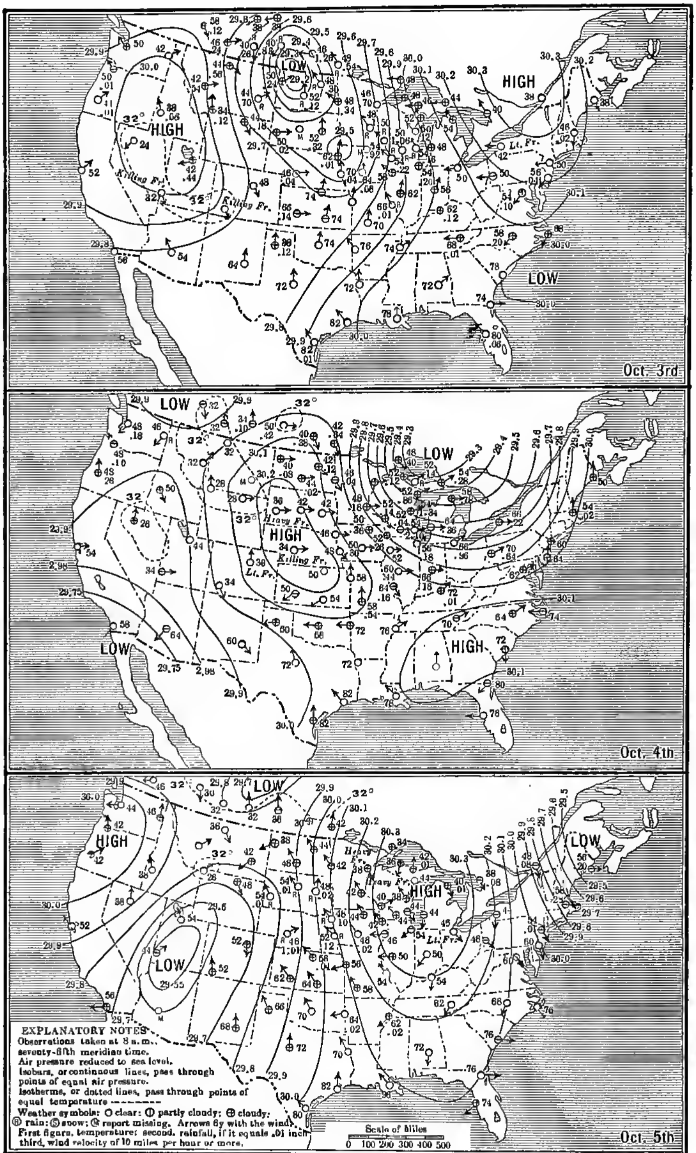


FIG. 498. — The temperature, pressure, wind, relative humidity, and rainfall during a hot summer day with an afternoon thundershower. (Milham.)



WILLIAMS ENGRAVING CO., N.Y.

FIG. 499. — Weather maps of three successive autumn days in 1913, showing eastward progress of a Low from Montana to Nova Scotia and a High from Nevada to the Great Lakes. (After U. S. Weather Bureau.)

example, there are times when the low pressure areas are so poorly developed that little rain falls for several weeks. During such a drought the smaller streams disappear, wells run dry, vegetation withers, and crops are retarded. At other times the low pressure areas may be so well developed that instead of scattered thunder storms there is general cloudiness and rain. In late summer and early autumn, when hurricanes pass up the Atlantic coast accompanied by strong winds and heavy rain, this condition of generally stormy weather is often developed.

Winter Weather in Eastern United States.—It has already been stated that during the winter the cyclonic circulation of the prevailing westerlies is better developed than during the summer, both anticyclones and cyclones being more frequent and more emphatic. As

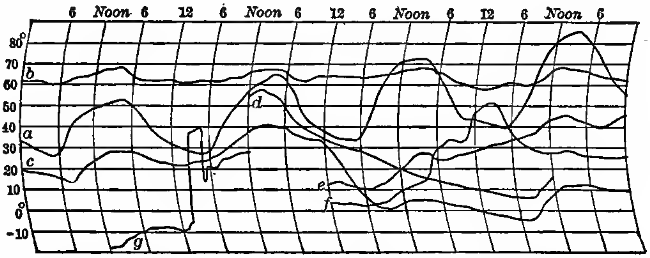


Fig. 500.—Thermograph records, *a* to *e* at Nashua, N. H., *f* at Cambridge, Mass., *g* at Fort Assiniboine, Mont. *a* shows a period of clear warming weather in April; *b*, cloudy weather accompanying a West Indian hurricane in September; *c*, change from moderate winter weather to a cold spell in February; *d*, steady fall of temperature from one January night to the next during approach of a cold spell in winter; *e*, steady rise of temperature in December; *f*, high temperature at night in November caused by warm southerly winds followed by cold westerly winds; *g*, sudden rise in temperature with hot, dry, chinook wind. (After Davis.)

they pass over the country (Fig. 501) they bring alternate clear and cloudy weather. The succession of cyclones and anticylones is sometimes so regular in winter that one day of the week may have nearly the same kind of weather for 2 or 3 successive weeks. It is this that gives rise to the belief that if it snows or rains on the first Sunday in a given month it will snow or rain on every Sunday in that month.

As the winter cyclones pass they may bring rain, or snow (Fig. 443). The velocity of the wind varies and the direction of the wind shifts through several quarters, so that when the wind is from the north there will be chilly weather, and when it is from the south there will be warm weather (Fig. 500). A thaw often occurs when the south wind is blowing in midwinter and many even cause rain to fall as far north as Canada. Often there is a decided drop in temperature immediately after a thaw, because an anticyclone follows directly behind the cyclone.

It is because of such changes as are outlined above that the climate

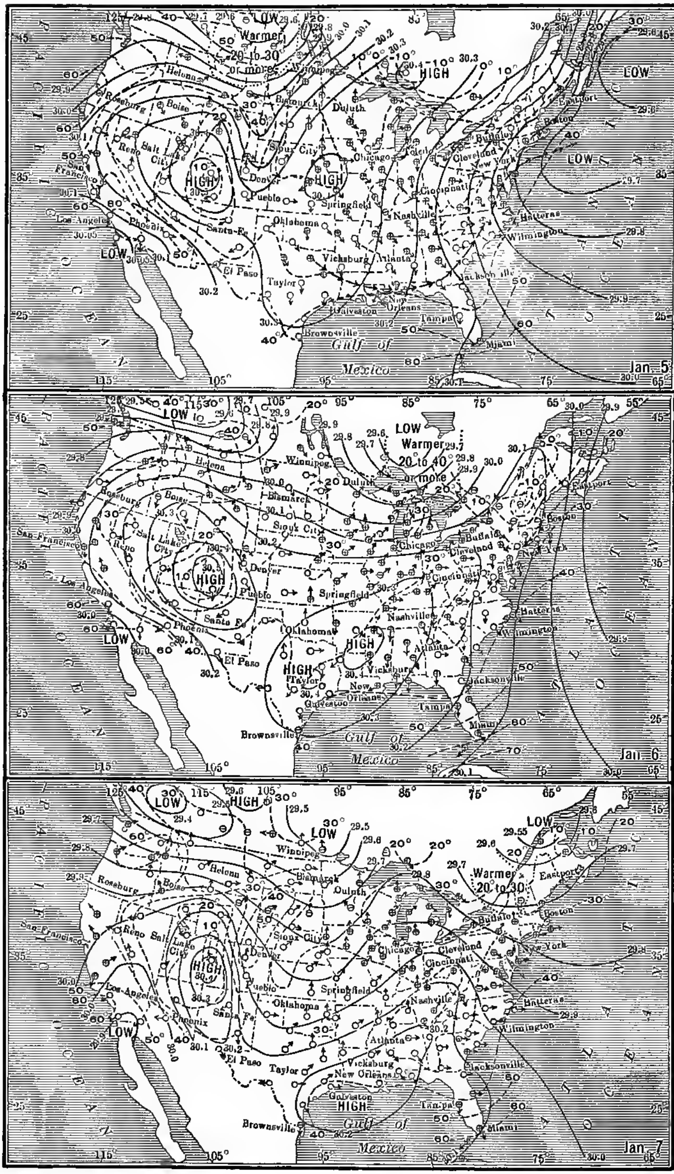


Fig. 501. — Weather maps of three successive winter days in 1914. Symbols as in Fig. 456. (After U. S. Weather Bureau.)

of eastern United States is spoken of as changeable and not temperate. There are few climates in the world characterized by such rapid changes of contrasting weather as the stormy west wind belts. These changes are trying to the health, and many diseases, such as grippe, pneumonia, and consumption are common in these severe climates.

Climate of West Wind Belt in Southern Hemisphere. — There is a striking difference between the climate of the north temperate zone and that of the south temperate zone, because the prevailing westerlies differ somewhat in the northern and southern hemispheres. The difference is chiefly because of the fact that there is far less land than water in the southern hemisphere. The changes in temperature in the south temperate zone are, therefore, less extreme than in the north. Over the smooth ocean, however, the winds blow with more strength and steadiness than over the irregular lands, so that they come to the land as stronger winds (Fig. 502). In other respects the climates of the north and south temperate zones are not very different. Over the southern ocean the weather is raw and cold in winter and damp and chilly in summer, although it does not have the extreme changes from warm to cold weather which we have in the northern hemisphere. In the south temperate zone the storms are frequent and fierce. It is because of this fact that the climate of the coast of southern Chile is rainier and more disagreeable than the climate of the

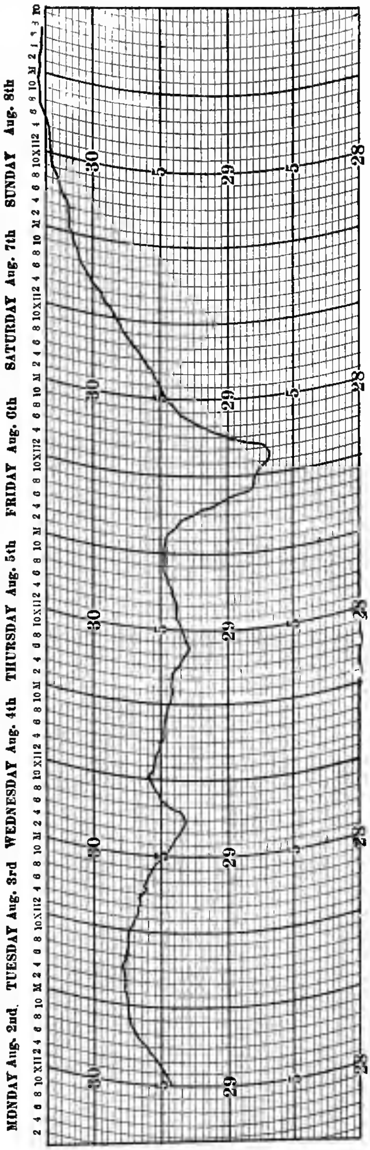


Fig. 502. — Barograph record of a week's winter pressure in the South Pacific during a journey from Punta Arenas at the Strait of Magellan northward to Corral, Chile. (Ward.)

coast of British Columbia and southeastern Alaska. Because of the velocity of the prevailing westerlies, or Brave West Winds, it is very difficult and often dangerous to go around Cape Horn at the extreme south end of South America, especially from east to west.

Polar Climates

Climate near the Arctic Circle. — North of the Arctic Circle the sun is above the horizon both night and day during the summer of the north polar zone. Accordingly, although the air is cool and sometimes raw, it is not very cold (Fig. 503). The ice melts out of the ground to a depth of 2 or 3 feet under the warmth of the sun, in places where the topography permits the thawing of soil, and the ground is therefore damp and swampy. In this season of the year in favourable places the grass becomes green, flowers blossom, and birds and insects appear. The summer weather is as changeable as in some parts of the belt of prevailing westerlies, however, because storms appear in fairly regular succession, bringing rain and snow squalls along the coast. On the sea, fogs are common at points where damp air is chilled in passing over cold water.

During the late summer when the sun ceases to be continuously above the horizon, the days grow cooler and the nights become very cold. The insects disappear, the birds take their flight to the southward, and the land becomes covered with snow. The ground is again frozen clear to the surface, and a skim of ice may appear on the ocean, becoming thicker as the days grow shorter. At this season the Eskimo of the north polar zone gives up the use of his skin boat, or *kayak*, and commences to use a dog sledge in hunting the seal, which furnishes his chief food.

When the time comes that the sun no longer rises above the horizon even at noon, the weather during both day and night is bitterly cold (Fig. 503). The principal changes in Arctic weather during the winter are those accompanying the passage of the cyclonic storms. Thaws are not unknown during the Arctic winter; and, even in midwinter, the temperature may rise high enough so that the Eskimo snow houses or *igloos* begin to melt.

When the sun reappears above the horizon in the spring, the snow melts and "frost" begins to go out of the ground. Then the Eskimo abandons his igloo for his skin tent or *tupic*. The floe ice in the ocean breaks up and floats away, so that the Eskimo uses his kayak instead of his sledge for hunting and travelling. This is the beginning of the long summer day of the Arctic.

Climate nearer the North Pole. — All the way from the Arctic Circle to the North Pole the men who have traversed the region found the climate similar to that just described, although farther north the Arctic winter night is longer and colder and the summer is cooler. Even in the northernmost lands the sun supplies sufficient heat during the summer so that the snow melts from much of the low ground near the coast. In the extreme northern part of Greenland, for example, Peary found flowers in blossom, insects humming about, and many musk oxen roaming over the land in summer.

The Arctic Ocean, the centre of which is the North Pole, is always covered with ice floes, even in summer, and it was over these that Abruzzi, Nansen, and other Arctic explorers travelled, and over which Peary finally reached the North Pole. He made his successful dash to the pole in early spring, because during the Arctic summer the ice is so much broken that it is difficult to cross it by sledges, and yet it is not broken enough so that ships may pass through. It was because of this fact that Peary learned through his many Arctic trips to go as far north as he could in a ship during one season and remain there during the cold Arctic night in order to be ready for an early start before the sun rose the second summer. The difficulties of travel over the ice and the exceedingly rigorous climate baffled the efforts of the hardiest and most venturesome explorers to reach the North Pole, until Peary was successful in doing so in 1908. The rigorous climate renders the lands nearest the North Pole an uninhabitable desert.

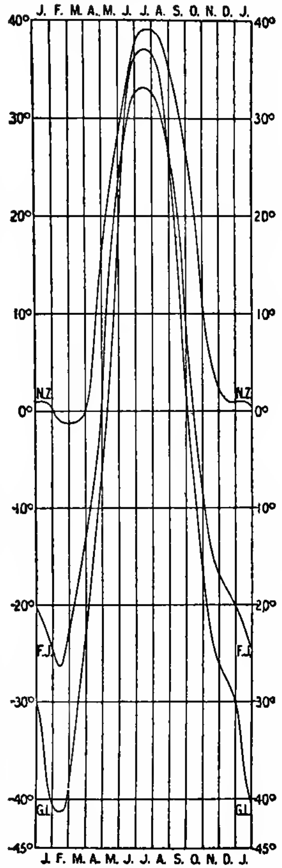


FIG. 503. — Seasonal range of temperature in the polar zone. (Ward.) N.Z. — Novaya Zembla; F.J. — Franz Josef Land; G.L. — Grinnell Land.

Antarctic Climate. — The climate of the Antarctic continent has become fairly well known in recent years through the many south polar expeditions, particularly those of Shackleton, Scott, and Amundsen. The striking difference between the Arctic and Antarctic regions is that the average summer temperature at the Antarctic Circle is about as cold as that at the North Pole in the Arctic Ocean. It should be stated, however, that both of these temperatures are rather moderate. The reason for the difference between the climate of the north and south polar regions is that the ice-covered land of the south polar continent gives very much lower temperatures than the slowly heating and slowly cooling water of the Arctic Ocean. The mean summer temperature on the coast of Antarctica is from 28° to 30° F., while the mean winter temperature is from 2° above zero to 15° below zero. These are the average summer and winter temperatures of the coast, not the extremes. The interior of the continent, rising to a height of 8000 or 10,000 feet, has a much more rigorous climate. At the South Pole there must be a continental climate, both because of altitude and because of the distance from the ocean. The summer temperatures encountered near the South Pole range from 0° F. to 35° or 40° below zero. The winter temperatures near the South Pole are much lower than this. Nine hundred miles from the pole at a point not far from the seacoast Scott recorded 77° below zero, F., in August, 1911, the heart of the Antarctic winter.

The Antarctic snowfall is surprisingly light, the amount at sea level near the border of the continent being estimated as not more than the equivalent of 7 to 14 inches of rain annually.

In the Antarctic region the winds of the prevailing westerly circulation attain great velocity at times, and these storms are followed by periods of calm. For example, when Amundsen was on his way to the South Pole in 1911, he had pleasant weather. Only a few weeks later, however, Scott, who also attained the South Pole, encountered such stormy weather that he was greatly delayed. At the pole itself there should, theoretically, be fine calm weather, and indeed Amundsen and Scott both found that at the pole the snow lay in horizontal layers without drifting, as if calm weather were the general rule there.

There seems to be a tendency to develop a foehn wind on the borders of the high plateau, with the air sliding outward down the slopes of the Antarctic continent. These winds often attain a velocity of 75 or 80 miles an hour. There are also severe blizzards, and it was in one of these that Scott finally lost his life on the return trip from the South Pole, at a distance of only 12 miles from a depot of supplies.

The severe cold, the blizzards, and the endless night of the polar winter limit the plant and animal life of the Antarctic continent to the very lowest forms; and there have never been human inhabitants in this region, except when exploring parties have temporarily spent a short time at the margin of the continent

References to Literature

J. G. Andersson and Others. Die Veränderungen des Klimas seit dem Maximum der Letzten Eiszeit, Stockholm, 1910, 459 pp.

H. Arctowski. Studies on Climate and Crops, Bull. Amer. Geog. Soc., Vol. 42, 1910, pp. 270–282, 480–495; *ibid.*, Vol. 44, 1912, pp. 598–606, 745–760; *ibid.*, Vol. 45, 1913, pp. 117–131; *ibid.*, Vol. 46, 1914, pp. 265–281.

D. P. Barrows. The Colorado Desert, Nat. Geog. Mag., Vol. 11, 1900, pp. 337–351.

J. G. Bartholomew, W. E. Clarke, and P. H. Grimshaw. Atlas of Zoögeography, Bartholomew's Physical Atlas, Vol. 5, Edinburgh, 1911.

I. Bowman. Man and Climatic Changes in South America, Geog. Journ., Vol. 33, 1909, pp. 267–278.

R. M. Brown. Indian Summer, Journ. Geog., Vol. 8, 1909, pp. 25–31.

Edward Brückner. Klimaschwankungen seit 1700, Penck's Geog. Abhand., Wien, 1890, 324 pp.
R. H. Chapman. The Deserts of Nevada and the Death Valley, Nat. Geog. Mag., Vol. 17, 1906, pp. 483–497.
H. C. Cox. Frost and Temperature Conditions in the Cranberry Marshes of Wisconsin, Bull. T, U. S. Weather Bureau, 1910, 121 pp.
J. Croll. Climate and Time, New York, 1890; Discussions on Climate and Cosmology, New York, 1886.
P. C. Day. Frost Data of the United States and Length of the Crop Growing Season, Bull. V, U. S. Weather Bureau, 1911, 5 pp.
E. G. Dexter. Weather Influences, New York, 1904, 281 pp.
H. N. Dickson. Climate and Weather, London, 1913, 256 pp.
R. E. Dodge. Climate and Mankind, Columbia University, Extension Syllabi, Series B, No. 4, New York, 1903, 19 pp.
H. Gannett. The Timber Line, Bull. Amer. Geog. Soc., Vol. 31, 1899, pp. 118–122.
A. W. Greely. American Weather, New York, 1888.
J. Hann. Handbuch der Klimatologie, 3d edition, Stuttgart, 1908; see also Ward's translation of Part I, New York, 1903.
M. Hardy. Oxford Wall Maps, 1909–1910: The World — Vegetation Regions, and vegetation maps of each continent separately.
M. W. Harrington. Rainfall and Snow of the United States compiled to the End of 1891, Bull. C, U. S. Weather Bureau, 1894, 80 pp.
A. J. Henry. Rainfall of the United States, Bull. D, U. S. Weather Bureau, 1897, 58 pp.; Climatology of the United States, Bull. Q, U. S. Weather Bureau, 1906, 1012 pp.
E. W. Hilgard. A Report on the Relations of Soil to Climate, Bull. 3, U. S. Weather Bureau, 1892, 59 pp.
E. Huntington. The Climate of the Historic Past, Monthly Weather Review, Vol. 36, 1908, pp. 359–364, 446–450; The Fluctuating Climate of North America, Smithsonian Report for 1912, Publication 2206, Washington, 1913, pp. 383–412; The Shifting of Climatic Zones as Illustrated in Mexico, Bull. Amer. Geog. Soc., Vol. 45, 1913, pp. 1–12, 107–116; The Pulse of Asia, Boston, 1907, 416 pp.; The Rivers of Chinese Turkestan and the Desiccation of Asia, Geog. Journ., Vol. 28, 1906, pp. 352–367.
Mark Jefferson. The Culture of the Nations, Bull. Amer. Geog. Soc., Vol. 43, 1911, pp. 241–265.
W. Köppen. Klimakunde, 2d edition, Leipzig, 1906, 132 pp.
C. H. Merriam. Life Zones and Crop Zones of the United States, Bull. 10, Division of Biological Survey, U. S. Department of Agriculture, Washington, 1898.
H. R. Mill. British Rainfall, annual volumes, 52d report, London, 1913.
R. C. Mossman. The Greenland Sea, Its Summer Climate and Ice Distribution, Scottish Geog. Mag., Vol. 25, 1909, pp. 281–291.
A. Penck. The Shifting of the Climatic Belts, Scottish Geog. Mag., Vol. 30, 1914, pp. 281–293.
A. Supan. Die Verteilung der Niederschlags auf der Festen Erdoberfläche, Gotha, 1898; Grundzüge der Physischen Erdkunde, Leipzig, 1911, pp. 230–257.
R. S. Tarr. Difference in the Climate of the Greenland and American Sides of Davis and Baffin Bay, Amer, Journ. Sci., Vol. 153, 1897, pp. 315–320.
E. T. Turner. Climate of New York State, Chapter XI in Tarr's Physical Geography of New York State, New York, 1902.
U. S. Weather Bureau. Climate and Crop Bulletins; Summaries of the Climatological Data for the United States by Sections.
J. Walther. The North American Deserts, Nat. Geog. Mag., Vol. 4, 1892, 163–176.
R. de C. Ward. Climate, Considered Especially in Relation to Man, New

York, 1908, 372 pp.; A Year of Weather and Trade in the United States, Pop. Sci. Monthly, Vol. 61, 1902, pp. 439–448; Suggestions Concerning a More Rational Treatment of Climatology, Report 8th International Geographical Congress, Washington, 1905, pp. 277–293; Two Climatic Cross Sections of the United States, Monthly Weather Review, Vol. 40, 1912, pp. 1909–1917; The Value of Non-instrumental Weather Observations, Pop. Sci. Monthly, Vol. 80, 1912, pp. 129–137; Hann's Handbook of Climatology, Part I, New York, 1903, 437 pp.

A. Woeikof. Die Klimate der Erde, Jena, 1887, 2 parts, 396, 445 pp.

INDEX